The Potential for Augmented Reality to Bring Balance between the Ease of Pedestrian Navigation and the Acquisition of Spatial Knowledge

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Abstract

Being completely lost in an unfamiliar environment can be inconvenient, stressful and, at times, even dangerous. Maps are the traditional tools used for guidance but many people find maps difficult to use. In recent years, new tools like outdoor Augmented Reality (AR) have become available which allow virtual navigation cues to be directly overlaid on the real world, potentially overcoming the limitations of maps. However, it has been hypothesized that lower effort invested in processing navigation guidance may lead to diminished spatial knowledge (SK) thereby making users of such navigation tools far more vulnerable to getting lost should the tools fail for any reason. This thesis explores the research question of how AR and maps compare as tools for pedestrian navigation guidance as well as for SK acquisition and if there is a potential for AR tools be developed that would balance the two.

We present a series of studies to better understand the consequences of using AR in a pedestrian navigation tool. The first two studies compared time-on-task performance and user preferences for AR and Map navigation interfaces on an outdoor navigation task. The results were not aligned with expectations, which led us to build a controlled testing environment for comparing AR and map navigation. Using this simulated setting, our third study verified the assumption that AR can indeed result in more efficient navigation performance and it supported the hypothesis that this would come at the cost of weaker SK. In our fourth study, we used a dual task design to compare the relative cognitive resources required by map and AR interfaces. The quantitative data collected indicated that users could potentially accept additional workload designed to improve SK without incurring significantly more effort. Our fifth and final study explored an interface with additional AR cues that could potentially balance navigation guidance with SK acquisition.

The contributions of this thesis include insights into performance issues relating to AR, a classification of user types based on navigation tool usage behavior, a testbed for simulating perfect AR tracking in a virtual setting, objective measures for determining route knowledge, the capacity that pedestrian navigation tool users may have for performing additional tasks, and guidelines that would be helpful in the design of pedestrian navigation tools.

Publications

- Andreas Dünser, Mark Billinghurst, **James Wen**, Villa Lehtinen, and Antti Nurminen. *Handheld AR for Outdoor Navigation.* In Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services, MobileHCI '11 - Workshop on Mobile Augmented Reality, 2011.

- Andreas Dünser, Mark Billinghurst, **James Wen**, Villa Lehtinen, and Antti Nurminen. *Exploring the use of handheld AR for outdoor navigation.* Computers and Graphics, 36(8): 1084–1095.

- **James Wen**, Mark Billinghurst, and William S. Helton. *A Study of User Perception, Interface Performance, and Actual Usage of Mobile Pedestrian Navigation Aides.* In Proceedings of 57th Annual of the Human Factors and Ergonomics Society Meeting, HFES 2013.

- **James Wen**, Mark Billinghurst, and William S. Helton. *Classifying Users of Mobile Pedestrian Navigation Tools.* In Proceedings of the Australian Conference of Computer Human Interaction, Oz CHI 2013.

- **James Wen**, Mark Billinghurst, and William S. Helton. *If Reality Bites, Bite Back Virtually: Simulating Perfection in Augmented Reality Tracking.* In Proceedings of the Computer Human Interaction Conference of New Zealand, CHI NZ 2013.

- **James Wen**, Agnes Deneka, Mark Billinghurst, and William S. Helton. *Fighting Technology Dumb Down: Our Cognitive Capacity for Effortful AR Navigation Tools.* Human-Computer Interaction: Applications and Services, Springer International Publishing, 525–536.

- **James Wen**, Agnes Deneka, Mark Billinghurst, and William S . Helton. *Really, It's for Your Own Good...Making Augmented Reality Navigation Tools Harder to Use.* In Proceedings of the Extended Abstracts of the 32nd Annual ACM Conference on Human Factors in Computing Systems, 1297–1302.

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Acknowledgments

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Though usually busy founding HIT Labs in various corners of the world, Tom Furness provided a most impressive demonstration of speed reading without seemingly overlooking any of the more inconspicuous details when he took a whirlwind tour of my dissertation and provided me with some insightful feedback in the critical eleventh hour. My journey might have been significantly curtailed had it not been for my erstwhile Middle Earth companion, Antti Nurminen from Aalto University in Espoo, Finland. While his impressive arsenal included no less than three GPS units for our journey up Mt. Victoria—which I will forever remember as, *There, Lost, Lost Again, Still Lost, and Back Again*—it was through his navigational mastery of the sometimes more abstract system of academic funding that allowed me to continue my research in Finland after Christchurch suffered two earthquakes that made the downtown area difficult—and, at times, impossible—to even visit, much less to conduct pedestrian navigation studies in the Name of Science.

Outside of the academic arena, I had the good fortune to have found some people that stayed with me through bad times as well as good and without whom I probably would not have survived my move to New Zealand, a place as far away from New York in spirit as it is in miles. In particular, I need to single out a few that have been pivotal during my time there. Naomi Clarke, her infectious energy and joyful demeanor coupled with a thoughtful compassion, lifted me from a depth I wandered into from which I felt powerless to emerge. Pretty much the first friendly guy I met after arriving as a stranger in a strange land was Josh van der Burg, who continues to be a dependable friend with both of us now coincidentally wandering the streets Göteborg as strangers in a new strange land. Caroline Forslund provided me with the Northern counterbalance I craved from time to time while living Down Under and pointed me in what she believed to be the right direction (that would be North) for my post doctoral endeavors even though that meant long, cold, windy, and wet winters for nine months of the year. There are just too many things that made Carsten Grimm my go-to guru so I'll just leave it at the Master of the Slow Cooker but he was definitely *the* man, absolutely there when I was flailing from all sorts of personal and academic demons, real or perceived. And, if there is one guy I would miss a flight for just to have yet another round of cheap beer—possibly to complain about the beer prices—it's James Guidera, the dancing feet of Wellington and grillmeister of Te Aro.

I would be remiss if I did not mention my family, who provided me with the opportunity to pursue my passion and I dedicate the time I've spent on my doctorate to two of my closest companions in my extended family, Rusty and Bobber. While I love learning and I feel fortunate to have been able to find such good tutelage during my time at Canterbury, some of the most important things one can learn in life come from sources of wisdom and compassion found outside the halls of academia and, dare I say, from outside of our own species.

Dedication

In loving memory of Rusty and Bobber

"For this invention will produce forgetfulness in the minds of those who learn to use it, because they will not practice their memory."

– Plato

1 Introduction

Long before content delivered on the internet was deemed to hinder our abilities to read beyond what would fit on a computer screen, concerns had been raised over advancing technology supplanting our more "natural" skills. As far back as ancient Greece, philosophers were lamenting over how the invention of writing would weaken memory as it threatened to replace the oral tradition of story telling. In more modern times, the introduction of the calculator was seen to have made us too lazy to hone our skills for doing basic arithmetic in our heads. But while most replacement of human skills by technologies cause no more than minor inconveniences—taking longer to calculate tips is, at worst, embarrassing—one convenient invention of our modern times may create a dependency that could arguably lead to dangerous scenarios in the absence of the tool: the mobile pedestrian navigation tool.

People often need navigation tools (e.g., maps) for areas they are not familiar with, and maps on smartphones and other mobile devices enable them to easily find their way. However, the loss of such guidance—due to battery drainage, lack of satellite signal, or other disruption—can lead to a state of disorientation that may broadcast the existence of a lost person to those around them who may have bad intentions. For a first visit, this would be a problem regardless of the navigation tool. Beyond that, one question of interest is:

How long do people need to use navigation aids before they can form a mental map strong enough so that no tool will be needed?

The purpose of a navigation tool is to guide its user to the desired destination; its impact on the formation of "mental maps" is not necessarily a critical component of its design. It can be argued, in fact, that the quicker a user is able to deduce the proper direction to follow when navigating, the better the tool is at fulfilling its function. Seen from this perspective, one of the more promising technologies for pedestrian navigation is *Augmented Reality* or simply, AR. AR seamlessly overlays virtual information into the real world environment so that instructions, directions, and annotations of every nature could be seen directly in a person's field of view, as shown in Figure 1.1. The technology was first developed in the 1960's and since then has been used in many different application areas including entertainment, medicine, and engineering. More recently, people have begun to explore the use of mobile and handheld AR systems for outdoor navigation.

AR technology allows guidance cues to be directly overlaid on the user's view so, at first glance, the ease with which directions can be interpreted appear to be far more efficient than having to interpret the symbolic representations of a standard map (see Figure 1.2). In this way, it has the potential to transform the stressful task of finding one's way in an unfamiliar environment into a simple act of merely following a virtual arrow painted on the ground.

Figure 1.1: Mobile AR technology, which projects virtual information onto the real world can be used for navigation guidance.

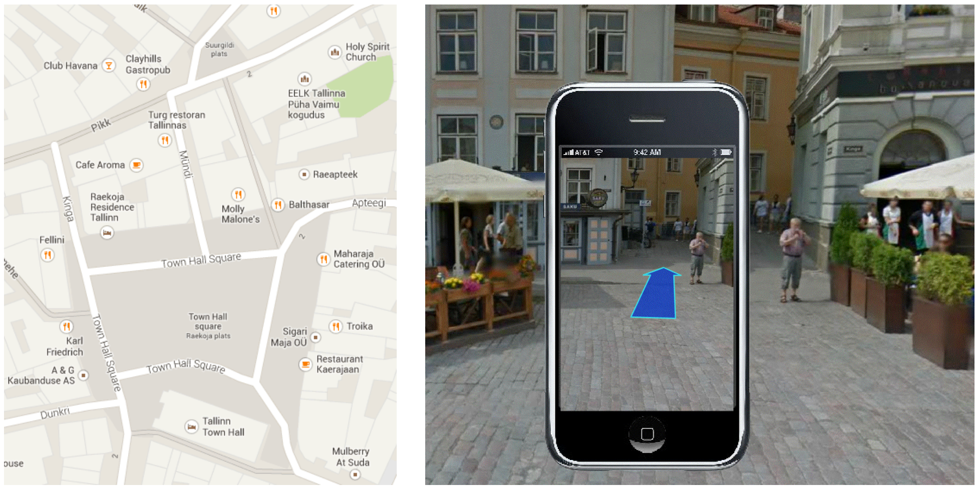


Figure 1.2: Map navigation tool (left) and AR navigation tool (right) for directions from the same location.

However, although AR technology appears to have the potential to make navigation easier, there have been very few formal user studies comparing navigation with mobile AR technology to more traditional map-based navigation. There has also been little work exploring how using AR for navigation affects the development of mental maps. Thus, the main research question we are exploring in this thesis is:

How does AR-based navigation compare to map-based navigation in terms of performance, mental map formation and cognitive effort required, and can AR tools be developed to improve recall of navigated paths?

Since AR is a new technology for navigation, this is an important research topic. It also encompasses a number of other important questions, such as: How will navigation with AR affect our innate abilities for unaided wayfinding? In particular, should the technology fail, for whatever reason, will the user be far more helpless than if they had relied on a more cognitively challenging navigation tool, such as a map that—even if it were lost to the wind—may have incidentally created a stronger impression of the navigable routes that may be recalled for later use? In other words, does the easy-to-use AR navigation system take away our ability to later recall our way around by ourselves? Is there a dependency created that make us less capable of learning our environment so that we can navigate independently? Is there a way to enhance the technology so that it can balance its efficiency in helping us navigate with helping us to gain a sense of our environment?

In this thesis we explore these questions from a Human Interface Technology perspective where elements of human behavior and cognitive resources are considered along with technology possibilities and development. By doing this, we hope to contribute to a greater understanding of AR-based navigation so that researchers may design pedestrian navigation tools that balances short-term effectiveness in guiding users with long-term benefits that will help users find their way unaided.

As will be shown in the rest of the dissertation, we make a number of important research contribution, including:

- Providing one of the first formal evaluations of mobile AR-based navigation compared to map-based navigation using typical AR browser interface

- Showing how user preference and perception of different mobile navigation tools align with actual usage

- Developing a number of novel methods for evaluating mental maps and navigation performance using AR and map tools

- Developing a classification scheme that can be used to categorize different types of pedestrian navigation tool users and inform the design of navigation tools

- Determining relative cognitive efforts required from AR and map users

- Designing and testing of an AR-based interface that seeks to improve mental map formation without sacrificing navigation efficiency

The heart of this dissertation comprises of five studies—detailed from Chapters 4 to 8—that addressed the research question and yielded the contributions given above. Many of these results have been published in peer reviewed conference and journal papers as shown below:

- *The following publications relate to the study of Chapter 4. In this study, the primary investigator was Andreas Dünser and it was he who took the lead role in the analysis of the data and in the writing of the papers. My involvement was as a co-experimenter who helped in the design of the study and conducted the study trials. I contributed to the technology as a secondary programmer, using a system that had been previously developed at the HIT Lab NZ. My role can be quantified as approximately 30% of the total work.*

  – Andreas Dünser, Mark Billinghurst, **James Wen**, Villa Lehtinen, and Antti Nurminen. *Handheld AR for Outdoor Navigation.* In Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services, MobileHCI '11 - Workshop on Mobile Augmented Reality, 2011.

  – Andreas Dünser, Mark Billinghurst, **James Wen**, Villa Lehtinen, and Antti Nurminen. *Exploring the use of handheld AR for outdoor navigation.* Computers and Graphics, 36(8): 1084-1095.

- *The following publications relate to the study of Chapter 5. In this study, I was the primary investigator and I designed and conducted the study as well as analyzed the data and authored the published papers. My role can be quantified as approximately 95% of the total work.*

  – **James Wen**, Mark Billinghurst, and William S. Helton. *A Study of User Perception, Interface Performance, and Actual Usage of Mobile Pedestrian Navigation Aides.* In Proceedings of 57th Annual of the Human Factors and Ergonomics Society Meeting, HFES 2013.

  – **James Wen**, Mark Billinghurst, and William S. Helton. *Classifying Users of Mobile Pedestrian Navigation Tools.* In Proceedings of the Australian Conference of Computer Human Interaction, Oz CHI 2013.

- *The following publication relates to the study of Chapter 6. In this study, I was the primary investigator and I designed and conducted the study as well as analyzed the data and authored the published paper. My role can be quantified as approximately 95% of the total work.*
  - **James Wen**, Mark Billinghurst, and William S. Helton. *If Reality Bites, Bite Back Virtually: Simulating Perfection in Augmented Reality Tracking.* In Proceedings of the Computer Human Interaction Conference of New Zealand, CHI NZ 2013.
- *The following publication relates to the study of Chapter 7. In this study, I was the primary investigator and I designed and conducted the study as well as analyzed the data and authored the published papers. My role can be quantified as approximately 95% of the total work.*
  - **James Wen**, Agnes Deneka, Mark Billinghurst, and William S. Helton. *How Technology Dumbs Us Down and How We Can Fight It: Cognitive Maps and Mobile Pedestrian Navigation Tools in a Digital World.* In Lecture Notes in Computer Science, Springer-Verlag. (*In press.*)
- *The following publication relates to the study of Chapter 8. In this study, I was the primary investigator and I designed and conducted the study as well as analyzed the data and authored the published papers. My role can be quantified as approximately 95% of the total work.*
  - **James Wen**, Agnes Deneka, Mark Billinghurst, and William S. Helton. *Really, It's for Your Own Good...Making Augmented Reality Navigation Tools Harder to Use.* In Proceedings of ACM Special Interest Group in Computer Human Interaction, CHI 2014 - Works in Progress.

In the next chapter, we will give an overview of the relevant background and related research conducted in this area that will help us to address these questions. In Chapter 3, we will discuss in greater detail the research question and research goals for this dissertation and show how the experiments presented in the thesis explore different aspects of the research question. Chapters 4 through 8 describe the experiments we conducted to address our research question and to reach our research goals. We will then discuss the lessons learned and the limitations of our thesis, as well as offer some guidelines from our work. We conclude this dissertation in Chapter 10 with some closing remarks and directions for future work.

2

Background & Related Work

This thesis is based upon the foundations of navigational theory, technologies for supporting pedestrian navigation, and an understanding of how we acquire the spatial knowledge needed to navigate without external aid. As such, it combines the work of several separate and distinct disciplines including psychology, computer science, geography and cognitive science. As an exploratory thesis, the scope of our original research evolved as we pursed our research goals. For the sake of clarity, we have divided the background material so that sections that are not relevant to the original thesis *per se* are presented in the chapters to which they are related. In this chapter, we provide a foundational base in the areas relevant to our original thesis as well as conduct a critical review of related work to establish the current state of knowledge and where the important research opportunities are.

2.1 Pedestrian Navigation Theory

The word "navigation" literally means "ship driving" (from the Latin roots *navis-* meaning ship and *-igare* meaning drive) and was first used in the late 16th century when Europe was at its height of seafaring exploration. Although the word continues to apply to vehicular guidance–such as Global Position Satellite (GPS) in-car navigation units directing drivers to local restaurants–the extension into pedestrian navigation, is a natural one. The constraints that govern the navigation of a vehicle, however, do not necessarily apply to pedestrians who enjoy far greater freedom of movement and are not subject to concerns relating to the rules of the road that are meant to prevent accidents [19]. This lack of constraints translates into a greater variety of interface possibilities [35], which makes pedestrian navigation a far more complex domain than vehicular navigation with respect to interface design [53].

At the most fundamental level, pedestrian navigation can be seen as a combination of *wayfinding*, which is the strategic process of movement planning, with *locomotion*, the physical act of mechanically orienting and transporting the body [13]. Depending on the level of refinement desired, models have been proposed that add varying degrees of details: subtasks for steering, aligning the surrounding environment with internal mental representation and, when the goal is near, employing situation knowledge to identify and reach the target [36].

Viewed with more structure, the act of navigation has been separated into four stages beginning with an initial orientation, which is followed by maneuvering and maintaining orientation, finally ending in target recognition [16]. Although we will divide the navigation task into small units for the sake of analysis, we will generally remain on a relatively high level of pedestrian navigation modeling and use the terms navigation and wayfinding interchangeably when a need to be consistent with relevant literature exists.

2.2 Spatial Knowledge

A central component of this thesis is how users of pedestrian navigation tools balance their navigational task with an acquisition of environmental knowledge. In his seminal work, Lynch [47] proposed that the perception of urban environments can be described by five fundamental physical elements (paths, edges, districts, nodes, and landmarks) which have three states of connectedness: unconnected, loosely connected, and solidly connected. These three classes of connections are reflected in the Landmark-Route-Survey (LRS) model that is widely used as the basis for various studies—including the ones in this dissertation—of spatial knowledge acquisition [81].

The LRS model states that spatial knowledge for an unfamiliar environment starts with a formulation of *landmark knowledge*, gained from recognition of landmarks, which can be used as visual cues for orientation. Greater familiarity with the area allows the disconnected landmarks to be joined by paths creating routes. Whereas landmark knowledge is simply a collection of disconnected nodes, *route knowledge* fills in some of the edges connecting some of the nodes. The possession of route knowledge gives one the ability to recall and re-traverse a path previously taken. As knowledge of the area continues to evolve and edges are further added, a complete graph is created and an overall knowledge of the area is attained. This is referred to as *survey knowledge* and it allows any two locations to be reached within the area regardless of actual visitation history.

Survey knowledge is often associated with the notion of a cognitive map, a concept that traces its origin to Edward Tolman and his pioneering use of laboratory rats in mazes [88]. How cognitive maps are represented or can best be judged is not clear and they may, in fact, have very little map-like elements but are based, instead, upon a wide and potentially rich set of memory mechanisms [81].

2.2.1 Measuring Spatial Knowledge Acquisition

The measurement of acquired spatial knowledge after exposure to a navigational task has generally been accomplished by assessing a participant's ability to estimate relevant distances and direction as well as create sketchmaps [20][24][56][100][101]. Distance estimates include straight-line distance as well as route distance. Directional estimates would generally involve pointing from one position to a known or previously visited position. Sketchmaps are meant to capture a person's configural knowledge of an area.

While such measurements have been in use for decades, inconsistent results from standard measurements have been found when environmental factors are altered—such as moving from an indoor setting to an outdoor setting [100]. Similarly, while studies of pedestrian navigation have utilized virtual environments for cost, safety and other considerations [15], the accurate transfer of cognitive maps and spatial knowledge have not been conclusively established [8][38].

It has been argued that route knowledge may be acquired even if survey knowledge is not [40], which is consistent with the LRS temporal model of spatial knowledge acquisition. However, it has also been argued that the three levels of spatial knowledge are acquired simultaneously in the act of actual traversal [11] and so route knowledge may not necessarily require landmark knowledge as a pre-requisite. Memory for routes may be reliant upon procedural memory and dependent on experiential factors; it has been shown that pedestrians who directly experience navigation tasks retain superior route knowledge when compared to map users [87]. Combined with the belief that aggregates of experiential and other non-spatial memories form the basis of path recall [29], there may be sound justification to use experiential measures where re-traversal of previously traversed paths is regarded as a way to judge route knowledge, as done in [34].

2.3 Pedestrian Navigation Tools: Maps and AR

The focus of this thesis is on GPS-enabled mobile AR-based pedestrian navigation tools, an emerging technology that has attracted early adopters but is, in many respects, only realizing a fraction of its potential given the accuracy of current infrastructure, as we will see in Chapters 5 and 6. In order to judge mobile AR as a wayfinding aid as well as measure its consequential impact on our ability to acquire spatial knowledge, we compare it against the traditional map.

2.3.1 Traditional and Digital Maps

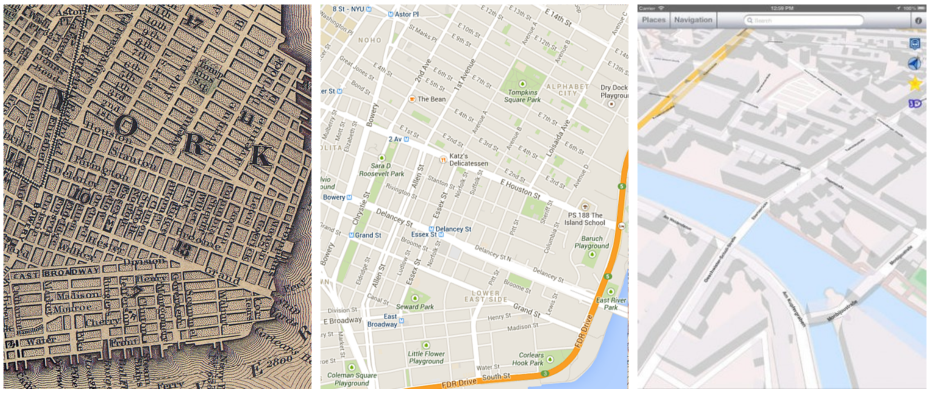
Paper-based maps have been used for centuries and are arguably the most common form of pedestrian navigational tools available.

However, while maps are universally recognized, proficiency in map reading is not universal: one in three people profess to have difficulties using maps [84]. This is because maps present cognitive challenges that the user must overcome, including:

- **Self-location** - Finding oneself on a map to begin the process of creating a navigation solution is often the initial task when consulting a map.

- **Landmark correspondence** - Associating the symbolic representation of real world landmarks with the actual structures in the surrounding environment can require a degree of concentration that may be easily disrupted by other pedestrians.

- **Mental rotation** - Rotating a paper map physically or mentally so that the direction



(a) Paper map (b) Digital map (c) Virtual bird's eye map

Figure 2.1: Maps.

of travel is aligned with the route depicted on the map relies upon a level of spatial ability that is confusing for many people.

Advances in computational power and sensor technologies have made possible digital enhancements to mobile maps that attempt to address these challenges.

Using location information from GPS data, dynamic You-Are-Here (YAH) markers rendered on top of maps can indicate where the user is within a digital map. The positional marker is updated continuously and eliminates the confusion people have when trying to locate themselves within a given map [45][76].

Possible solutions to associating symbolic map representations with physical landmarks include superimposing a video feed of the real world directly onto maps [44] and using computer graphics to create virtual 3D maps [48] [72] [39]. The use of 3D building outlines is already available in a wide variety of existing mobile applications but it has been found that users of 3D maps often have frustrating problems adjusting their viewpoint, which can diminish the effectiveness of such tools [65].

With the integration of compasses into mobile devices, maps can dynamically align with the direction the user is facing. Such maps are referred to as Forward-up maps and they can vastly improve map-guided performance [79][80][96].

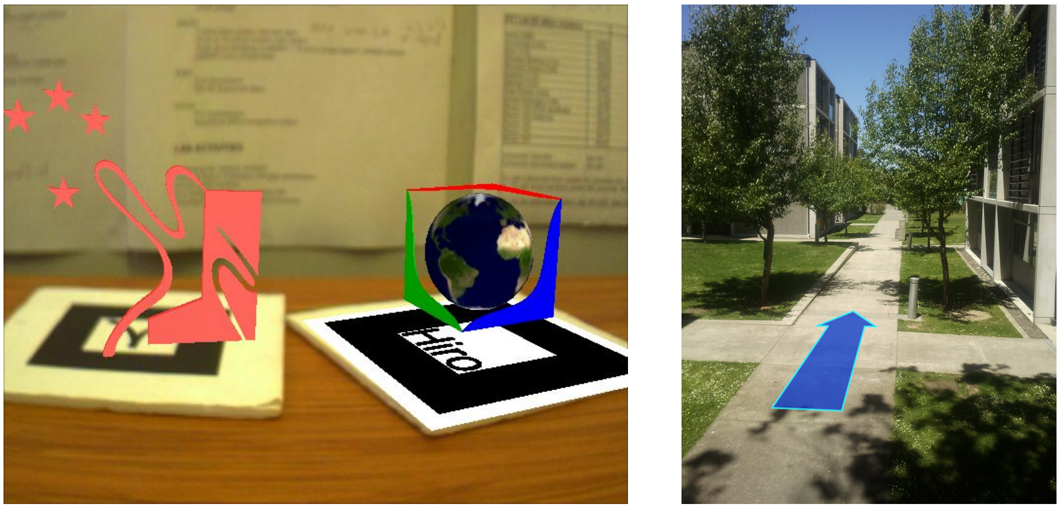
While these solutions can be combined into an interface that addresses the problems of traditional maps, a solution that is potentially far more elegant and intuitive is AR. At its full potential, AR practically eliminates the notion of a separate and distinct navigation tool altogether by simply augmenting the reality around a user with guidance information that appears as a part of the scenery.

2.3.2 AR Navigation Tools

As seen in Chapter 1, AR overlays virtual information on top of the surrounding real world environment. The real world can either be seen directly through a transparent surface upon which the AR information is projected (e.g., see-through glasses of Figure 2.3) or indirectly by way of a live video stream through a camera (e.g., through the video shown on the screen of a mobile device as in Figure 1.2.

In order to maintain the illusion that the virtual objects actually inhabit the real world environment, the technology needs to *track* the movement of device so that the virtual objects can be rendered in place accurately. Tracking is generally divided into two types: image-based and location-based. Image-based tracking may use markers that are recognized by the AR software. Using computer vision techniques, the known size and orientation of the marker can be compared against the visible marker so that the position and orientation of the camera on the mobile device can be geometrically calculated. This makes it possible for objects to be accurately projected and rendered in the 3D scene (see Figure 2.2(a)). Location-based tracking renders virtual objects based upon GPS position data to indicate the position of the AR device combined with sensor information related to device orientation. While image-based tracking is mature enough for the commercial market, location-based tracking is still limited to large-scale scenes that are not sensitive to the inaccuracies in GPS data. Current research combining markerless natural feature image-based tracking, internal device sensor data, and GPS information seeks to address the shortcomings of location-based tracking but such systems are not yet ready for the general market.

Our work in this thesis with AR-based navigation is based upon the expectation that accurate location-based tracking for standard mobile devices will be realized in the near future. There are many examples of work in this area that preceded ours. One of the



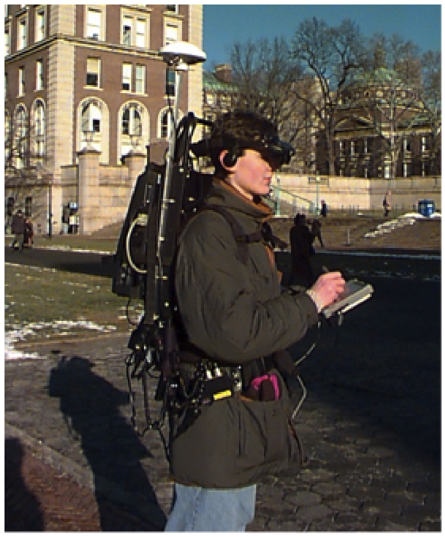
(a) AR image tracking. (b) AR location tracking.

Figure 2.2: The two methods of tracking in AR.

earliest mobile AR systems was the Touring Machine, which used a head-mounted display that allowed a user to walk around an urban environment and see buildings labeled with their functions [18]. This was followed by a number of portable, if similarly cumbersome, AR navigation systems, such as [86] and [44].

As AR interfaces become more streamlined and commercially viable—and location-based tracking issues are suitably resolved—AR pedestrian navigation tools could be an attractive alternative to map-based tools. This is because, by the nature of how AR is used, it could overcome the fundamental usage challenges of maps, as mentioned in Section 2.3.1. Firstly, self-location is not an issue since the perspective of an AR tool is centered around the user. Landmark association is also eliminated since AR uses the actual surrounding environment—rather than representations of it—as the backdrop of its interface. Finally, AR tools dispense with alignment issues altogether since, by the nature of AR, the device is aligned with the direction of travel. In this way, AR should provide a sharp contrast with maps and, in our thesis, such a contrast may help to highlight effects we hope to study.

Despite the potential advantages AR offers over maps, to the best of our knowledge at



(a) Mobile AR circa. 1996

(b) Mobile AR circa. 2012

Figure 2.3: Portable AR systems have come a long way.

the time of our research, no studies have been undertaken to compare mobile AR pedestrian navigation tools with maps in terms of performance or usability. Moreover, when comparative evaluations of mobile pedestrian navigation interfaces are done, they are generally designed as studies where users experience one interface at a time rather than have the option to choose between interfaces. The lack of such studies for mobile pedestrian navigation tools in general—and for AR in particular—makes it difficult for us to properly assess AR. This is particularly true since AR also has its drawbacks such as the need for a user to keep track of the virtual Point-of-Interest (POI), turning around physically at times to scan the environment for relevant POIs. The sustained attention needed to keep AR objects in view may cause fatigue and distract a user from interacting with the actual surrounding environment, which has raised concerns that important information in the real world may be overlooked due to the need to focus on using AR [1]. Studies have indicated that users may have preference for AR navigation guidance most heavily just before and after decision points, such road intersections [59] and it has been proposed that denying users of continuous AR in favor of on-demand AR may be preferable since it minimizes divided attention which may affect acquisition of spatial knowledge [21].

2.4 Navigation Tools and Spatial Knowledge Acquisition

Burnett and Lee [10] proposed a relationship between spatial knowledge and navigation task demands. As depicted in Figure 2.4, map users start with high task demand but the

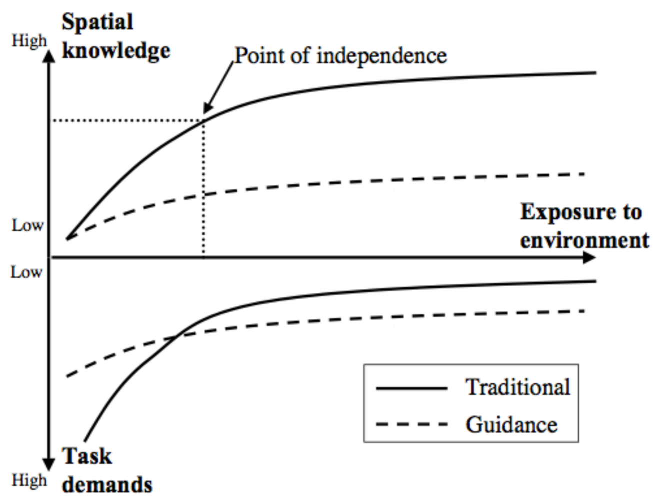


Figure 2.4: Relationship between task demands and spatial knowledge acquisition as proposed by Burnett and Lee.

demand drops over time as spatial knowledge develops. In contrast to this, users guided by turn-by-turn directions start with lower task demands but the task demands do not reach the levels ultimately reached by traditional users since spatial knowledge does not develop as much. Their model was based upon observing drivers with vehicular navigation systems and they concluded that use of such systems will have a negative impact on cognitive map formation. However, as the authors noted, their study did not include demand and performance measurements, which would be a necessary next step since those are the traditional metrics of the domain. Further, as a study with drivers, the process of navigating as well as the nature of the navigation tool are potentially very different from what a pedestrian would experience.

Willis et al. [100] noted that the "switching off" of mental processing by users of navigation tools—who are essentially being led without having to make self-motivated choices—does not support learning in a constructive manner. To increase user awareness they proposed transforming the passive nature of navigation tool usage into an active interactive process where users are required to confirm navigational information mid-task. They also suggested reducing the lack of reference between the navigation tool and the real world by forcing users to manually match cues. Although sensible in theory, they neither implemented nor tested their proposed solution.

In a study deployed as a virtual world, Parush et al. [68] attempted to address the degradation of spatial knowledge acquisition due to automated navigation systems by "keeping the user in the loop." They did this by requiring the user to request navigation information actively rather than have it delivered automatically and continuously, hypothesizing that continuous positional information will yield superior wayfinding performance but degraded spatial knowledge. They also sought to engage users by issuing occasional orientation quizzes, which did not degrade wayfinding performance but forced users to invest greater mental effort which resulted in better learning. However, they did not measure time-on-task performance but measured the distance traversed based upon the logic that excess distance was indicative of the effectiveness of the navigation tool. While this is sound reasoning, it neglects time spent considering the available options but which ultimately do not result in different traversal solutions. Further, since users were given orientation quizzes, the fact that they performed better in the subsequent test of spatial knowledge through directional questions may be surprising. Their performance on directional questions may be indicative of the advantage gained by the similarity of the quizzes with the measure rather than actual improvement in spatial knowledge.

Water and Winter [97] conducted a similar study to diminish a navigators dependency on navigational tools by imbuing a training role to the tools. This was done by adding landmark cues to automatically generated route directions as well as omitting constant orientation updates to encourage users to turn their attention to their surrounding environment. The study was conducted on-line in order to collect a large sample of 124 participants. The participants were shown an experimental video of the route. They were judged on their ability to subsequently recall landmark sequence and map correctness based on whether a given map matched the route and, if not, what the incorrect parts were. No significant differences were found between the conditions. In addition to the possibility that such enhancements to the navigational tools may actually have no effect, the authors note that the on-line nature of the experiment may have introduced confounding factors. Further, a video traversal may not capture enough of the navigational experience and a traversal in a real or virtual world may provide a needed disorientation threat.

Münzer et al. [60] measured both spatial knowledge gained and wayfinding accuracy, defining wayfinding accuracy as the number of wrong turns taken. They compared three interfaces: a 2D map showing the entire area, a 3D map with turning directions rendered as arrows, and a compass interface that showed all the waypoints in a radar–like layout. They found that the 3D route map resulted in the lowest wayfinding and scene recognition errors but also resulted in the worst sketch maps and the poorest directional estimates. 2D map users created the best sketch maps but performed worst in scene recognition. Compass users fared worst in wayfinding but best in direction estimates. The sketch maps created by compass users were scored only slightly lower than those created by 2D map users, but were statistically equivalent. The hypothesized that there is a tradeoff between navigation wayfinding effectiveness and acquired survey knowledge.

To the best of our knowledge, no studies investigating the impact of AR navigation tools on the formation of cognitive maps were done prior to the commencement of this dissertation. However, after the thesis was begun—and unbeknownst to us at the time we were conducting our first study—Huang et al. [30][31] in Vienna, Austria, conducted a similar experiment based upon the premise that spatial learning is an effortful process and so poor results in spatial knowledge acquisition would be observed given the relatively effortless nature of AR interfaces. They reported that participants performed poorly in all of the given tasks for assessing spatial knowledge including recognizing visited landmarks, recalling turns made, and correctly associating landmarks with locations. Thus, to date, no conclusive results have been found with AR navigation interfaces with respect to its impact on the formation of cognitive maps.

It can be seen from this review of the relevant literature that no conclusive evidence exists to confirm assumed trade-off between navigation support with the formation of spatial knowledge with respect to AR pedestrian navigation tools.

2.5 Research Gaps

Our background and literature review revealed some gaps in prior research. No user evaluations had been conducted to compare performance between map-based and AR-based pedestrian navigation tools and so there is no actual data to support the assumption that AR could be a more efficient pedestrian navigation tool. Furthermore, no usability studies had been undertaken to compare map-based and AR-based pedestrian navigation tools in terms of performance, mental map formation, and the relationship between the two. Consequently, the notion of one tool being "easier" than the other cannot be taken for granted when seeking to determine if the use of an easier tool will impact upon the formation of cognitive maps. Also, while the relationship between navigation support and formation of cognitive maps has been examined for maps and a variety of navigation interfaces—both practical and contrived for the research—it has not been examined for AR-based navigation tools. Finally, studies that attempt to include spatial knowledge building features have not been tested with AR-based navigation tools. We will expand upon these gaps in the next chapter where we identify our research goals for this thesis.

2.6 Summary

In this chapter, we laid the groundwork for the research into our thesis. We first provided a summary of the theory behind pedestrian navigation within urban environments that has elements from both geography and environmental psychology. We followed that with an overview of spatial knowledge acquisition and mental map formation which have their roots in cognitive psychology. We then took a brief survey of the two navigation technologies relevant to this thesis that may represent, in many ways, opposite ends of the navigation tool extremes: maps and AR. Having laid the foundation in the relevant areas for our research, we proceeded to undertake a critical review of research related to how pedestrian navigation tools may impact upon the formation of route knowledge which is summarized in Table 2.1.

Study	**Highlights**	**Gaps**
Burnett and Lee (2005)	Stress helps SKA Paradigm shift needed to focus on SKA	No measurements made for demands or performance
Parush et al. (2007)	Withhold continuous guidance Pop directional quizzes	Measured distance and directional memory No time-on-task measurement
Willis et al. (2009)	Users “switch off” so no SKA Proposed forcing users to be active	Theory only No studies conducted
Waters and Winter (2012)	Withhold continuous guidance Provided landmark cues	Used video playback No threat of getting lost
Münzer et al. (2012)	Tradeoff hypothesis between navigation and recall	Measured sketchmaps and turn recall No performance measures

Table 2.1: Summary of critical review

While our coverage provides a foundation for our overall thesis, more specific background material related to the individual studies rather than to the overall thesis will be provided in the appropriate chapters for which they are applicable. Our treatment of the relevant background in this chapter serves to guide and inform us in the pursuit of our thesis and, in the next chapter, we will formulate our research goals based upon our fundamental interest and the gaps we have found in the literature.

3

Research Goals

Our literature review from the previous chapter revealed a number of research gaps that will need to be addressed in order to advance the thesis of this dissertation. In this chapter, we formally present our research question which was introduced in Chapter 1. We then refer to the research gaps identified in Chapter 2 and lay out our research goals followed by the associated hypotheses we intend to address specifically in our user studies.

3.1 Research Question

Our research question can be posed as follows: *How does AR-based navigation compare to map-based navigation in terms of performance, mental map formation and cognitive effort required, and can AR tools be developed to improve recall of navigated paths?*

This question has two parts: first, comparing AR-based to map-based navigation tools in terms of performance, mental map formation and cognitive effect, and second, exploring new AR tools that could be used to improve recall of navigated paths. To address this question there are a number of research goals that will need to be addressed, such as comparing baseline performance of map and AR navigation tools, tool usage patterns, and measuring the cognitive demands of the different tools. In this chapter we explain in greater depth the main research goals we are interested in, hypotheses we can make based on previous research, and experiments that we have conducted to explore these hypotheses.

We should note that we limited the scope of our research to comparing two pedestrian navigation tools: AR-based and map-based in order to define an overall research goal that would answer our research question while still being tenable. We further constrain our study to urban environments, which include buildings and other potentially distinctive landmarks that could aid in forming cognitive maps. Finally, we restricted our judgment of cognitive maps to the acquisition of route knowledge, which may not be as powerful as survey knowledge (see Section 2.2) but is arguably more relevant for recalling a path to take.

3.2 Research Goals

Based on the overall research question, there are a number of research goals that we will aim to achieve. The first is to obtain time-on-task measures of AR and map navigation tools based upon actual targeted search tasks in an outdoor urban environment. This is important because we need to calibrate our work in accordance with an understanding of how such tools perform in actual use cases in the wild so that we may compare navigation effectiveness with spatial knowledge acquisition.

Research Goal #1: Establish a baseline performance measurement of map-based and AR-based pedestrian navigation tools for primed searches.

In our research we assume that the improved performance of AR-based pedestrian navigation tools would occur at the price of acquiring route knowledge and so we need to compare the two quantities. This leads to our second research goal:

Research Goal #2: Compare route knowledge acquisition between users of map-based and AR-based pedestrian navigation tools.

Our research question rests, in part, on the perceived ease-of-use of AR-based pedestrian navigation tools. We define, as our next research goal, an investigation into user perception of pedestrian navigation tools. In particular, we wish to observe how users judge pedestrian navigation tools and compare such subjective data with how they actually use the tools available. By offering a variety of navigation options, we can see if user perception aligns with actual usage. In this way, we can gain insights into how the ease-of-use of a tool is perceived and how it affects usage behavior.

Research Goal #3: Collect data in order to compare user preferences with actual usage behavior when a choice of pedestrian navigation tools is available.

Because one of the main measures of workload demand is based upon subjective user surveys, we will also want to better understand how different types of users may behave. While usage behavior is based on individual differences and may change from user to user, designing tools will require a broader understanding of user types. One approach is to give due consideration to user behavior on a larger scale by classifying similar users into groups that have well defined preferences that could guide design. Another research goal, then, is to create a classification for users of mobile pedestrian navigation tools.

Research Goal #4: Analyze usage data in order to create a classification of pedestrian navigation tool user types.

User preferences is generally based on user perception, which in turn, is based upon subjective measures (e.g. SUS and TLX questionnaires - see Appendices G and F). However, the building of route knowledge is dependent upon user awareness of the surrounding environment and such awareness is highly dependent on the effort users need to devote to the navigation tool. It is therefore important to find a more objective measure of the cognitive demands of pedestrian navigation tools beyond subject surveys. This leads to our fifth research goal:

Research Goal #5: Find an objective measure of the relative demands imposed by map-based and AR-based navigation tools.

Finally, an area rich with possibilities is exploring how to balance navigation tool convenience with a stronger formation of cognitive maps. We base our last research goal on the promising work examined in Section 2.4 indicating potential in balancing navigation functionality with spatial knowledge acquisition. Specifically, we follow the approach of [68] but, instead of using a contrived directional quiz that may have limited practical usage we add in more practical landmark cues used by [97] and supported by [3][49][51][77]. Our final research goal, then, is:

Research Goal #6: Attempt to use AR to define landmark-based cues in a request-based pedestrian navigation tool that seeks to improve the acquisition of route knowledge without sacrificing guided traversal performance.

Exploring these research goals will help us to better understand how AR-based navigation compares to map-based navigation. Based on the previous related work, for each of the research goals we have arrived at a hypothesis that can be tested. These are discussed in the next section.

3.3 Hypotheses

In pursuit of the research goals, given above, we formulate a set of corresponding hypotheses that we will test in a series of experiments. As previously noted, AR could resolve many of the challenges that make maps difficult to use. Consequently, we expect people using AR to perform faster than people using maps. This forms the basis for our first hypothesis.

> **Hypothesis 1 (H1)**: The time-on-task performance measure for outdoor wayfinding tasks will be better (i.e., shorter) for an AR-based mobile pedestrian navigation tool than for a map-based tool.

As discussed in Chapter 1, better performance achieved with AR-based tools (as proposed in H1) may come at the price of weaker cognitive maps. We base our next hypothesis on this notion.

Hypothesis 2 (H2): Users of an AR-based pedestrian navigation tools will acquire route knowledge that is, on average, weaker than users of map-based pedestrian navigation tools so AR users will require more time or make more errors than map users when attempting to recall previously traversed paths.

As described in Chapter 2, pedestrian navigation can be seen as a series of steps with subtasks including orientation and target recognition. It seems reasonable to argue that the subtasks will have different importance depending on the phase of navigation (e.g., goal recognition is more important towards the end of the navigation task) and, as a result, may be better addressed by different navigation interfaces. We hypothesize that usage preferences may change within a navigation task depending on the perceived phase of navigation. That is, users may prefer one kind of tool at the beginning of a navigation task but switch to another type of tool when approaching the destination.

Hypothesis 3 (H3): Mobile pedestrian navigation tool usage within a navigation task would favor some tools over others depending on the phase of navigation.

Recognizing that individual preferences may play a significant role in how users perceive pedestrian navigation tools and their usability, we believe we can classify users in order to better understand how tools can be designed for the different target groups.

Hypothesis 4 (H4): Usage behavior can be used to create user groupings that could indicate significant differences in preferences with respect to pedestrian navigation tools.

We expect that the greater ease-of-use associated with AR-based pedestrian navigation tools will lead to less cognitive resources needed and, consequently, more cognitive resources available for other tasks. This is something that can be measured with objective means and we believe that using a dual task approach as in [23] will yield useful metrics. This leads to our next hypothesis:

> **Hypothesis 5 (H5)**: When compared to users of a map-based pedestrian navigation aid, users of an AR-based pedestrian navigation aid will, on average, exhibit better results in performing unrelated and simultaneous secondary tasks without sacrificing performance on the primary wayfinding task.

We wish to explore the possibility of enhancing AR-based pedestrian navigation tools in order to help users acquire better spatial knowledge and we hypothesize that we can do this by adding spatial knowledge building features.

> **Hypothesis 6 (H6)**: Introducing cues for improving spatial awareness to users of AR-based pedestrian navigation aids will improve route knowledge for traversing the same path.

Each of these hypotheses will be explored through one or more user studies. These are described in the next five chapters and in Appendix H. Table 3.1 shows how the research goals and hypotheses given above relate to the next several chapters in this dissertation.

As will be seen, some unexpected results were obtained and, as a consequence, we have had to undertake additional work that was unforeseen when we established our original research question. We were, however, able to achieve results that helped us advance knowledge and understanding of this area. In the next chapter, we begin our journey with our first study, which had a goal of verifying our assumption that AR-based pedestrian navigation tools would be an obvious choice for users who wish to find their way quickly and easily.

Research Goal	Related Hypothesis	Relevant Experiment
RG1	**H1**	Nav1 (Chapter 4) Nav3 (Chapter 6) Nav4 (Chapter 7) HMD (Appendix H)
RG2	**H2**	Nav3 (Chapter 6) Nav4 (Chapter 7) HMD (Appendix H)
RG3	**H3**	Nav2 (Chapter 5)
RG4	**H4**	Nav2 (Chapter 5)
RG5	**H5**	Nav4 (Chapter 7)
RG6	**H6**	Nav5 (Chapter 8)

Table 3.1: The research goals, their associated hypotheses, and the related studies

4

Nav1: Comparative Performance Study for Maps and AR in an Outdoor Environment

In order to establish a baseline understanding of the differences in pedestrian navigation between map-based tools and AR navigation tools, we designed a comparative study that evaluated user performance. In this chapter, we describe the study, our findings, how we interpreted the results, and how it relates to the overall thesis. To the best of our knowledge, this is the first study that has been conducted comparing map-based, AR-based, and the combination of the two tools, using AR interfaces based on those found in typical AR browsers. By establishing a baseline performance measurement, we can explore the differences between these two forms of navigation tools and the impact they have on navigation effectiveness and spatial knowledge acquisition. We refer to this study as Nav1 and it addresses research goal RG1 (see Section 3.2) and hypothesis H1 (see Section 3.3).

4.1 Introduction

Our thesis explores the effectiveness of AR navigation tools for wayfinding and cognitive map formation. In this chapter, we describe an experiment we conducted to compare the performance of two navigation interfaces: maps and Augmented Reality. These two tools have important differences in interface design for pedestrian navigation tools. Paper maps have been the *de facto* accepted means of navigation guidance for centuries and modern digital maps have substantially retained their features and effectiveness. AR navigation tools, on the other hand, are a more recent invention and have no classical counterpart.

Operating from a first-person ego-centric perspective, AR addresses some of the most challenging aspects of traditional maps, such as mental rotations (causing people to rotate maps to align them with the direction they are facing) and representation correspondences (where graphically representations on a map need to be matched to real world scenery and landmarks). Returning to our research question, we ask: will the simplicity introduced by AR navigation tools diminish the formation of cognitive maps that may have been more easily formed as a result of the greater mental effort required when using maps? Our search for the answer to this begins by looking at whether AR tools produce better wayfinding time-on-task performance.

4.2 Background

We began our research at a time when consumer mobile devices had enough computational power to provide GPS-based outdoor AR experiences. AR Browser software such as Junaio [1], and Wikitude [2] were available on popular devices such as Apple's iPhone and Google's Android handsets. Such software were promoted as tools to guide users to nearby cafes, museums, bus stops or other POIs, as shown in Figure 4.1. More than half of all mobile device searches have been identified as searches for directions: 52% of searches were target location-based searches and 21% of the searches had specific places given [85]. Thus there is an opportunity for new mobile technology such as AR browsers to help with navigating to POI.

Users searching for location-based information from mobile devices generally want to find their way to the POI and, while the AR tools are able to show users the location of the POI, it is not clear how effective this information is for supporting real world navigation. The two

[1] http://www.junaio.com/

[2] http://www.wikitude.org

(a) The Junaio AR navigation browser (b) The Wikitude AR navigation browser

Figure 4.1: Two currently available mobile AR browsers

	Maps	AR
Perspective	Third Person	First Person
Viewpoint	Exocentric	Egocentric
Representation	2D Graphical	Real World and Projective 3D

Table 4.1: Usage differences between maps and AR

interfaces we wanted to compare are fundamentally different, as shown in Table 4.1: maps provide a pre-rendered, top-down exocentric view of the environment while AR provides an egocentric view of the real world with virtual location-based information rendered over it in real-time, as shown in Figure 4.2. It follows that the usage style and user behavior of these two interfaces would potentially be different.

Our aim was to explore the resulting differences in effectiveness based upon the affordances and limitations of existing systems widely available to the general public at the time of the experiment. To the best of our knowledge, at the time of this research, practically no work has been undertaken to evaluate the differences in navigation by AR compared to more traditional tools, such as north-up maps. We did not want to make improvements upon the interfaces or provide new functionalities outside of what was already available in the consumer market. Rather, we hoped to be able to better understand how different

(a) Exo-centric map tool

(b) Ego-centric AR tool

Figure 4.2: Map vs. AR navigation tools

interfaces impact actual navigation. Would users follow substantially different routes based upon the information provided by the different navigation tools? Would performance be enhanced in certain situations and suffer in others depending on the user interface?

From this study, we hope to gain some foundational understanding of the differences in navigational usage and performance. Since our study is one of the first comparative outdoor navigation studies using a handheld AR system, we expect it would also provide valuable information for designers and researchers who are developing similar systems.

4.3 Study Design

We conducted a user study to evaluate user performance, satisfaction, and navigation behavior in an outdoor navigation task. We employed a within-subject design where each participant was given three separate navigation tasks in succession. Each task took place along a unique path with different target destinations and each task utilized a different navigation tool condition. Although we did not have enough participants to eliminate order effects, combinations of interface conditions and navigation paths were administered according to an orthogonal Latin-square to reduce order effects, as shown in Table 4.2.

Participant	Trial 1		Trial 2		Trial 3	
1	AR	a	Map	b	AR + Map	c
2	AR + Map	b	Map	c	Map	a
3	AR	c	AR	a	Map	b
4	Map	c	AR + Map	b	AR	a
5	AR + Map	a	AR + Map	c	AR	b
6	Map	a	Map	b	AR + Map	c
7	AR	a	AR	b	AR + Map	c
8	AR + Map	b	Map	c	Map	a
9	AR	c	AR	a	Map	b
10	Map	c	AR + Map	b	AR	a
11	AR + Map	a	AR + Map	c	AR	b
12	Map	a	AR	b	AR + Map	c
13	Map	a	AR	b	AR + Map	c
14	AR + Map	b	AR	c	Map	a
15	AR	c	AR + Map	a	Map	b
16	Map	c	AR + Map	b	AR	a
17	AR + Map	a	Map	c	AR	b
18	AR	a	Map	b	AR + Map	c
19	AR + Map	b	AR	c	Mao	a
20	Map	a	AR	b	AR + Map	c
21	AR	b	AR + Map	c	Map	a
22	AR + Map	b	Map	c	AR	a

Table 4.2: Task completion time and distance traveled

4.3.1 Traversal Paths

Our study took place on the campus of the University of Canterbury in Christchurch, New Zealand. The campus environment reflects an urban setting to the extent that buildings and man-made footpaths dominate the landscape. The experimental routes were designed to be predominately within the campus area so vehicular traffic was not a major concern. By minimizing vehicular interference, we would be able to focus on issues specifically relevant to pedestrian navigation.

Three different paths were created for users to follow, each with a sequence of four destination targets spread around the university campus area, as shown in Figure 4.3. The targets were all separated by at least one turn and at least two decision points where turns are possible but not necessarily the correct option to follow. We took care to ensure that the targets were connected by highly visible roads, streets, or footpaths even though less obvious options existed and participants were free to follow those. The destination targets were chosen to be between 100m and 300m apart and the overall path lengths were all approximately 800m. Since the participants were not confined to stay on the pre-determined paths, the actual distances they traversed could vary depending on how they used the navigation tools.

Figure 4.3: Paths used; POIs shown as yellow dots with green rims; path a (magenta), path b (orange), path c (cyan).

4.3.2 Interface Conditions

We were interested in how people navigated outdoors in three different interface conditions:

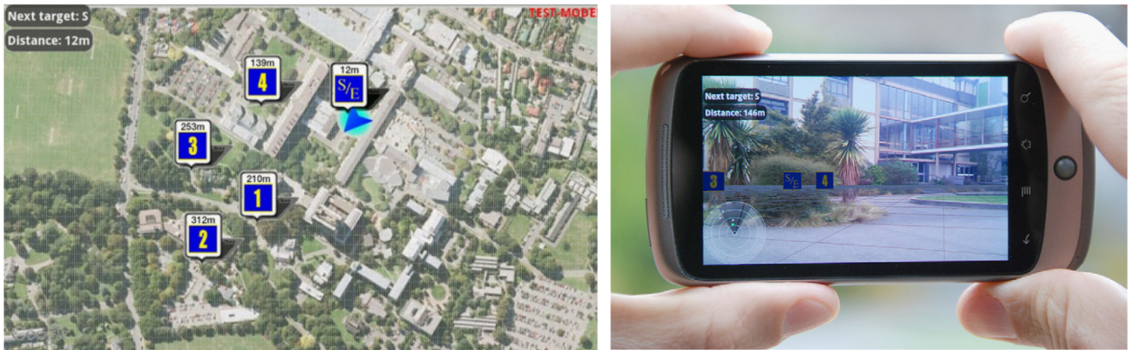
- Map: Using only a top down, exocentric 2D map view;
- AR: Using only an egocentric AR view; and
- Combination: Using both Map and AR view.

The particulars of the technology underlying the navigation interfaces will be described in a subsequent section. Here, we will examine the design of the user experience with respect to the navigation interfaces of our study.

Both the Map and the AR interface displayed a message at all times indicating the numeric identification of the current target and the distance to it. When the user is within 10m of the target, a popup message was shown indicating that the current target was reached.

The Map interface is a north-up map where the top of the map is always aligned with compass-north. (This is in contrast with forward-up maps, which has no traditional counterpart, and is based upon technology that automatically aligns the map with the direction that the user is facing.) The Map interface provided standard pan and zoom interaction that allowed the participant to use finger gestures to see any part of the map and to see all, some, or none of the targets on-screen at any time. This is shown in Figure 4.4(a).

The AR interface functioned as a see-through window into the surrounding environment enhanced with visual cues that indicated relevant information overlaid on live video of the real world. As a navigation tool, the relevant information would include the current destination, which is rendered as a virtual object in the real environment as seen through the device's screen. The participant will have to scan the surrounding area until a target is within the field of view, in which case it would be rendered and visible on screen. If no targets are within the field of view, the participant will have to turn the device until a target is within the field of view. A radar interface is included in the lower left corner of the AR view to indicate where the target destinations, or Points of Interests (POIs) are with respect to the participants. This is shown in Figure 4.4(b).



(a) The Map interface (b) The AR interface

Figure 4.4: The two navigation interfaces

It should be noted that, for the Map interface, the participant could hold the device in whatever position that is comfortable for use without disrupting the functionality of the map. The AR interface, on the other hand, is only effective if the participant holds the device vertically upright so that the live camera feed of the real world can usefully capture the area of interest (which presumably would include the paths the participant can follow as opposed to the sky or the ground).

The Combination interface condition allows the participant to freely switch between AR and Map interfaces at any time. An option to switch from the current interface to the alternative interface is shown at all times at the top of the screen. The user is neither encouraged to nor discouraged from exercising the option but is told that it exists in case they felt certain situations were more amenable for one interface over the other.

In all cases, based upon the information shown on the device, the participant is expected to decide upon a way to reach the current target and to physically walk to the target.

4.4 Technology Implementation

In order to test the performance effectiveness of standard features in actual use while still maintaining control over experimental needs, such as data logging, we developed our own mobile navigation application based upon interfaces and properties available in existing popular systems.

4.4.1 Hardware

We built our system on an Android-based HTC Desire A8181 mobile phone using a Qualcomm QSD8250 Snapdragon chipset with a 1 GHz Scorpion CPU. The Android operating system was upgraded to 2.2 (Froyo) for our experiment. The device featured a 3.7 inch screen with a 800x480 resolution and included a 5 megapixel camera capable of capturing video with a 320x240 resolution at 30 frames per second. There was GPS support as well as an on-board compass and accelerometer. During our experiment, we found the average GPS accuracy to be 7.02m (SD = 3.95) with a maximum error of 48m and a minimum error of 2m.

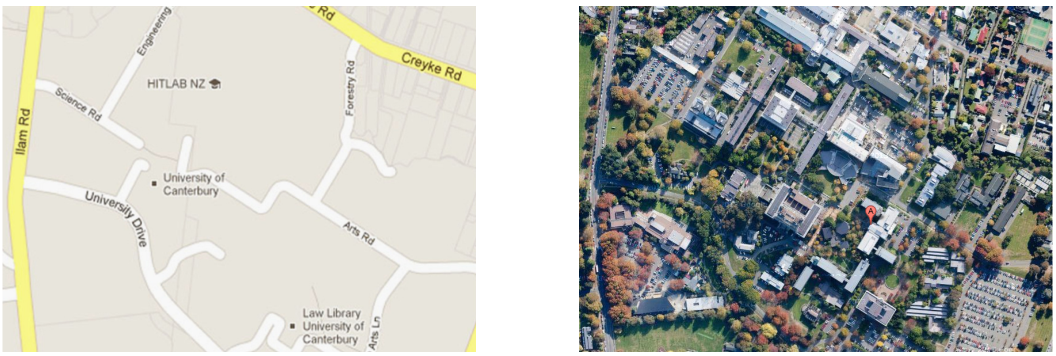
Although sensor reading and movement of the hardware in terms of position and orientation could be captured, it did not necessarily follow that a user actually paid attention to the navigation tool while handling the device. We therefore mounted a camera on the device so that it would point at the user whenever the display of the device was facing the user. In this way, we can gather information on where the users were looking while using the device. A standard webcam was used and it was attached to a UMPC the user carried in a small shoulder bag during the navigation task. Additionally, the experimenter accompanying the participant used a handheld video camera to record each trial.

4.4.2 Software

The test application supported two main modes of navigation assistance: a map-based tool and an AR-based tool, which formed the two main conditions of the experiment. A third condition offering both interfaces in a combination mode where the user was free to choose either interface at any time was also tested.

Map Interface

We used the Google Maps API to build our map interface. Our study was designed over the campus at the University of Canterbury so we were concerned that many paths and walkways may not be represented in the database. While existing cartographic maps such as Google Maps, Bing Maps, and OpenStreet Maps, showed major streets, they did not show footpaths or building details, as shown in Figure 4.5. Since satellite images depicted the sort of detailed information for a campus setting that would help users choose paths that may otherwise not be represented, we decided to consider using those for our Map interface.



(a) Cartographic map. (b) Aerial image

Figure 4.5: Standard cartographic maps of the area used in the study did not show footpaths and walkways that users could follow in the aerial map.

A drawback to a satellite-image based map was that additional cartographic information was not provided—e.g., photographic aerial images do not emphasize potential routes or walkways. On the contrary, many navigable areas are occluded by large trees, vegetation, and man-made structures, making wayfinding more difficult. The dense unfiltered information may also be more difficult to absorb when compared to graphics designed to highlight navigable paths. However, aerial images do have the syntactic property of representing a landscape as seen from above and the semantic property of depicting features with a small degree of abstraction [7]. Given a large enough scale where individual features can be recognized, it was been observed that even small children can infer correspondences between aerial photographs and the real world in order to perform spatial tasks [70]. We therefore felt that satellite images were a reasonable choice upon which to base our Map interface condition.

The sequence of target locations were shown on the map interface as pins fashioned after the standard pins rendered on typical digital maps. Within each pin is a number identifying the target in the sequence of targets. The distance to the current target is shown in an information bar on the top left hand corner of the screen. Available real-time GPS data and the Android Location Manager libraries provided the information to render a You Are Here (YAH) marker, shown as a highlighted arrow. The direction of the arrow indicated the orientation of the user and was based upon the device's accelerometer and compass data accessed through the Android Sensor Manager libraries.

AR Interface

The AR interface was built on top of HIT Lab NZ's Android Outdoor AR platform, which is a set of Java libraries for developing Android applications.[3] The libraries, shown in Figure 4.6, include:

- Low level modules: Software for reading data from location sensors, capturing camera input, rendering graphics, networking, etc.;
- Middleware: A unified library that provides a single programming interface to the low level software (e.g. architectural module, navigation module, etc.); and
- Application Layer: Final end user application (including specific assets).

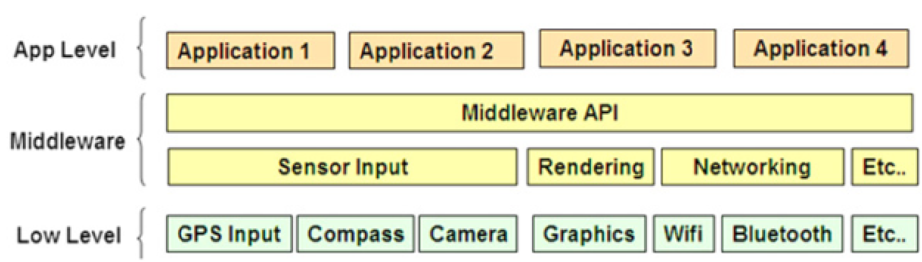


Figure 4.6: The HIT Lab NZ Android AR platform.

[3]http://www.hitlabnz.org/index.php/products/mobile-ar-framework

The virtual targets overlaid on the live camera view were simple cubes with textures showing the sequential number of the target within the target sequence. The OpenGL ES 2.0 3D engine was used to create the 3D models. The textures were all pre-loaded into memory upon first access of the AR mode so as to reduce rendering latency during usage.

Each target cube was rendered in perspective and to occupy the actual location in three-dimensional space so that its projected screen size was dependent on the user's distance relative to it. To ensure that the targets did not entirely disappear from view due to the perspective-based rendering, once a user was more than 50 m away from a target, the target was replaced by a 2D billboard image that retained its visibility regardless of user distance. This is shown in Figure 4.7.

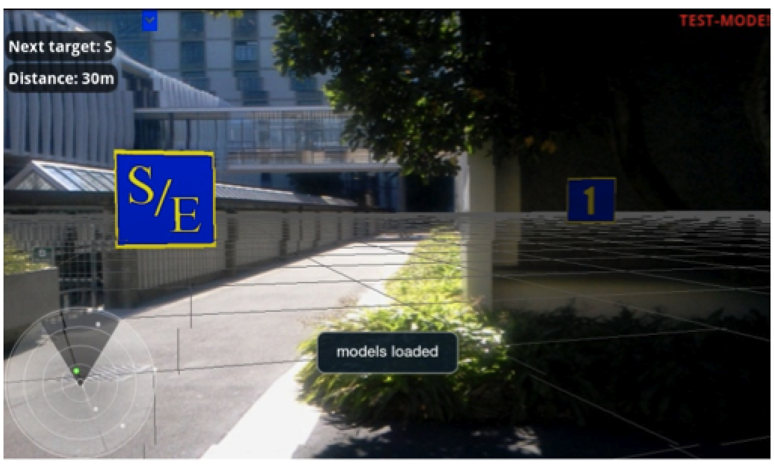


Figure 4.7: The AR interface showing the virtual targets.

An artificial grid rendered on the bottom of the screen represented the ground plane and helped the user in evaluating the distance of the virtual objects by providing an extra depth cue. A radar-view, similar to ones found on standard AR applications, was included on the bottom left corner of the screen and showed the distance and directions to all the target locations. Finally, the number of the current target and the distance to it were shown on the information bar in the upper left corner of the screen.

For the Combination interface condition, an additional button for switching modes was available at the top of the screen.

Additional Technology Enhancements

Our system supported features for data capture including the logging of time, location (longitude and latitude), orientation (pitch, roll, yaw), the current target, and the interface used at a given time. The logs were recorded at a rate of one entry per second. We also constrained the device use to landscape mode, in part to avoid complications with the mounted camera. All hardware buttons were disabled with the exception of the home and menu button, which could not be disabled.

4.4.3 Subjective Data Collection

Before starting on the navigation tasks, the participants were asked to complete a demographics questionnaire as well as answer questions relating to mobile phone and GPS-navigation application use experience. After each interface condition, the participants were asked to fill out a usability questionnaire as well as a NASA TLX survey for the interface just used. Both the pre-test and the post-test questionnaires are given in Appendix A. At the end of all three conditions, participants were asked to rank the interfaces in order via the following four questions:

- 1. Which condition did you prefer?
- 2. Which condition allowed you to perform best?
- 3. Which condition got you to a POI the fastest?
- 4. Which condition got you to a POI with the least errors?

4.5 Results and Analysis

In this section, we report on the data collected for the objective measures of performance, the subject measures of questionnaire responses, and the analysis of video footage for the study.

4.5.1 Participants Recruited

A total of 22 participants (11 females) were recruited for the study ranging in age between 19 to 47 years (M = 31.8 years, SD = 8.0). We selected participants that had minimal knowledge of the campus environment and who had little or no prior experience with mobile AR applications.

4.5.2 Performance Results

Navigation Time

Task completion times and traversed distances were recorded and analyzed with a 2-factorial ANOVA with interface type as a within-subjects factor and gender as a between-subjects factor. There were no significant differences detected in the time taken to complete navigating the paths between the three interface conditions ($F(2, 38) = .25, p = .78$). There were also no significant differences found in the distance traversed between the three interface conditions ($F(2, 38) = .80, p = .46$). Table 4.3 shows a summary of the overall navigation times and distances.

Examining the times and distances for each interface condition over the three paths, we found some significant differences within interfaces that varied across the paths. The AR interface trials showed a significant difference between the paths in completion time ($F(2, 19) = 3.73, p < .05$) and distance traversed ($F(2, 19) = 4.14, p < .05$). As can be seen in Figure 4.8, the completion time for Path C was significantly higher than the completion times for Path A and Path B with the AR interface. No significant differences existed for completion times between paths for the Map interface. For the Combination interface, there was a significant difference in completion times between paths, with Path A having a faster time than the other two paths ($F(2, 19) = 4.87, p < .05$).

Environmental Analysis

By superimposing the recorded geo-location data over images of the experimental area, we were able to examine the actual routes taken by the participants, as shown in Figure 4.9. From the figure, it can be seen that the paths walked contain several features that are

	Time (sec)			Distance (meters)		
	Mean	MD	SD	Mean	MD	SD
AR	953	855	344	1339	1208	414
AR + Map	968	932	275	1286	1253	305
Map	919	870	271	1220	1220	281

Table 4.3: Task completion time and distance traveled

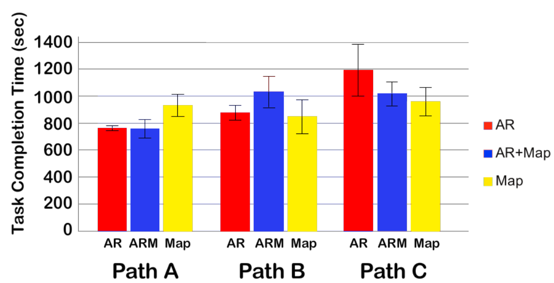


Figure 4.8: Task completion time for the three paths.

not very obvious without an area overview. For example, a path that appears to be a thoroughfare from ground level may actually turn out to be a dead end, terminating within an enclosed space of a large building. When using the AR interface, several users walked down such paths not knowing that there was a building or some other obstruction blocking the most direct path between the POIs. Referring again to Figure 4.9, it can be seen that, between POIs 1 and 2 (shown as yellow dots), some participants had to backtrack after taking a route that led to a dead end. This did not happen to participants using the map interface and occurred only once with the Combination interface.

While the AR interface misled participants down dead end routes that the Map interface avoided, it may also show short cuts that are less visible from a top down aerial view. Between POIs 2 and 3 in Path C, also seen in Figure 4.9, three AR interface participants and four Combination interface participants took a short cut that was not clearly visible from the Map interface due to tree cover. Only one Map interface participant took the short

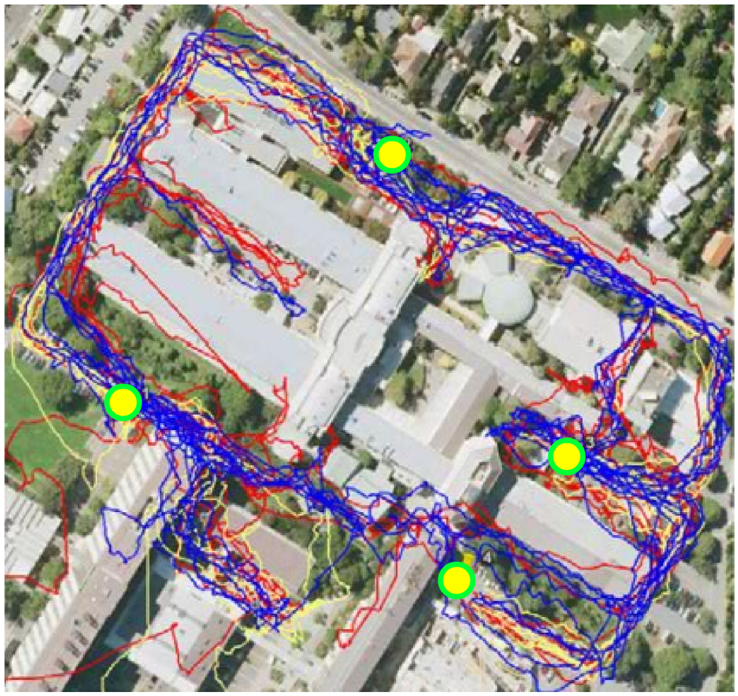


Figure 4.9: Actual traversal routes taken by participants for Path C. POI's are represented by yellow dots. Paths by map users are shown in yellow; AR users in red; and Combination (AR and Map) in blue.

cut.

Gender Analysis

We observed significant differences between genders in task completion times ($F(1, 19) = 4.42, p = .05$) and in distance traversed ($F(1, 19) = 9.56, p < .01$). Overall, women took longer to complete the navigation task and travelled longer distances. Significant interaction between interface and gender for task completion time ($F(2, 28) = 3.52, p < .05$) indicates that female participants took longer to navigate the paths using the Map interface as well as the Combination interface. No significant differences were found between the sexes for the AR interface. This is shown in Figure 4.10. Actual AR usage time in the combination mode did not exhibit any significant differences between male participants (52%) and female participant (55%).

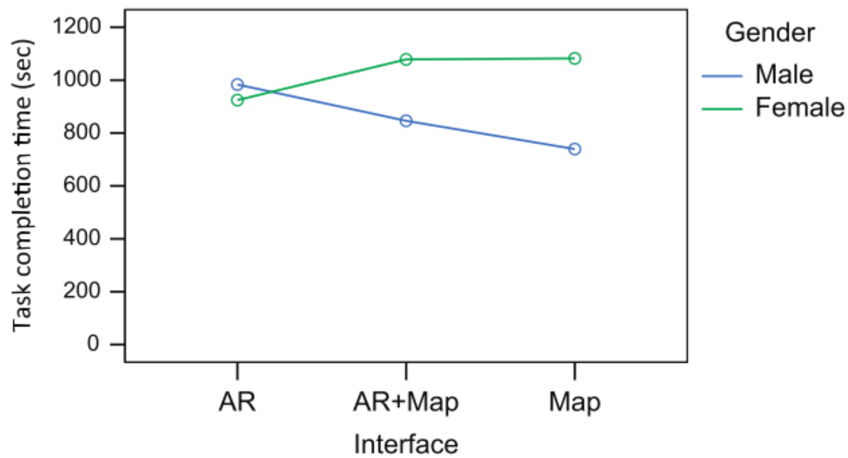


Figure 4.10: Interaction effect between interface and gender for task completion time.

4.5.3 Questionnaire Results

Results from the usability questionnaire completed after each interface condition are shown in Figure 4.11.

In the post-test questionnaire, the Combination interface had the highest average ranking for all the questions while the Map interface was ranked second each time, and the AR interface scored lowest each time. This is shown in Figure 4.12. Significant differences were detected for Question 1 (*Which condition did you prefer?* ($\chi^2 = 12.09, df = 2, p < .01$), Question 3 (*Which condition got you to a POI the fastest?* $\chi^2 = 6.09, df = 2, p = .05$), and Question 4 (*Which condition got you to a POI with the least errors?* $\chi^2 = 14.27, df = 2, p < .01$).

The questionnaires and NASA TLX were analyzed using Friedman tests. The data showed that the AR interface was perceived to be significantly less useful than the Combination interface for completing the task ($\chi^2 = 10.30, df = 2, p < .01$). There was also a preference for the Map or Combination interfaces over the AR interface for use in everyday life ($\chi^2 = 6.90, df = 2, p = .03$). None of the other differences were significant and there were no gender differences. We also did not find any significant interface effects or gender differences in the NASA TLX questions.

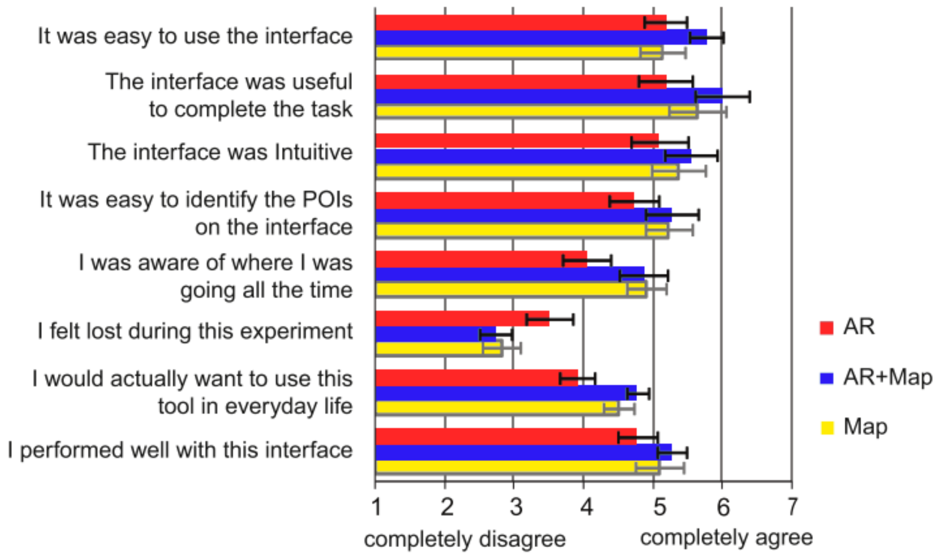


Figure 4.11: Results from the post-test questionnaire.

4.5.4 Video Analysis

We analyzed the video footage taken from the webcam facing the user by coding frequencies and times of user looking at the device screen, stopping, and looking for navigation cues in their surrounding environment. This is shown in Figures 4.13 and 4.14.

The number of times users looked at the screen was very similar across the interfaces: 62 for the Map interface, 54 for the AR interface, and 58 for the Combination interface. On the other hand, the amount of time spent looking at the screen varied somewhat: 335s for the Map interface, 306s for the AR interface, and 393s for the Combination interface.

The number of times users stopped to assess the surrounding environment—presumably to orient themselves—was averaged with the Map interface yielding 12 stops, the AR interface also yielding 12 stops, and the Combination interface yielding 9 stops. Similar to the screen viewing time, the amount of time users stopped to look at the surrounding environment also followed a somewhat different pattern from the frequency of stops: 85s for the Map interface, 59s for the AR interface, and 74s for the Combination interface.

Referring again to Figure 4.13 and 4.14, it can be seen that the biggest differences

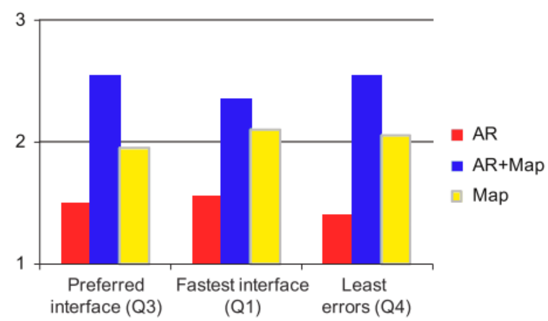


Figure 4.12: Average interface ranking frequencies (1=least, 3=most).

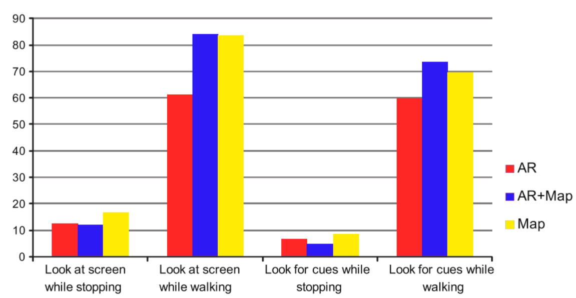


Figure 4.13: Number of times users looked at the mobile device.

were observed for participants looking at the screen while walking: participants stopped, on average, 83 times over 416 s with the Map interface, 61 times over 331 s with the AR interface, and 83 times over 502 s with the Combination interface.

4.5.5 Participant Comments and Experimenter Observations

Participants were asked to provide feedback using a written comment box on the post-test questionnaire as well as the opportunity to have verbal comments recorded. Experimenters who accompanied the participants kept records of noteworthy observations made during the trial. Here, we present the feedback categorized by the three interface conditions, usage experience, and gender differences.

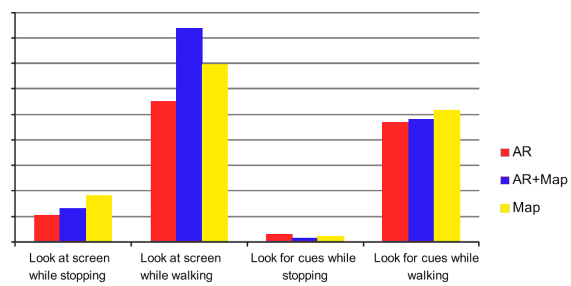


Figure 4.14: Amount of time users looked at the mobile device.

Map interface

Participants were all familiar with maps—if not necessarily comfortable with them—through exposure to traditional paper-based maps or in-car GPS navigation systems. Several participants felt that the biggest advantage of the Map interface was that it gave an overview of the area and showed where they were in relation to the surroundings. “I found the map interface the best one to use because you are actually able to see the physical objects around you and the hazards which you are going to come across whereas with the AR mode, you had no idea if there was a building in the way.”

However, not all participants liked the map view. As one participant noted, “The thing that I disliked about the map interface was that you saw it from above because that disoriented you.” Another participant commented on the north-up map orientation: “I had problems with the map because I’m used to my TomTom in my car which turns the map for me while I drive. Whichever way you go, that is what you see.” The tree cover that was inherent in the aerial imagery was a navigation factor, as well: “...the vegetation was blocking most of the potential paths so I didn’t know if I could go through or not. Also, I couldn’t know if a building had a walkway and if I could walk underneath or not. So for my route decision, I had to just go around, at least in that path where I was using the map.”

AR Interface

Many users mentioned being lost with the AR interface. One participant expressed concern about the limited scope of AR: “I found it quite hard to get to some of the targets because I didn’t know the way to get to them. I didn’t know if there would be a dead end.”

A number of users noted that the radar cue was a useful orientation aid and some even said they relied more on the radar cue than the actual AR view with the virtual POIs: “I found the radar really helpful and I used that most of the time. It was only when I got within 30-40m of where the target was, that I started to scan the area and look for the actual target cube. The radar was a good replacement for the map.” One female participant commented on preferring the AR interface because “It was more visual, I didn’t know the area as well so that kind of showed me a better direction to follow.”

For some, the AR interface seemed to require more attention from the users than the 2D interface: “AR required me to be fully interactive, meaning I wasn’t concentrating on my surroundings like roads/people, etc.” Another participant noted, “I had a problem with being oriented with the AR interface. I felt very disoriented, very lost because I was trying to concentrate on where to go by looking at the phone but then I had no idea what was around me so I didnt know where exactly I was going.”

Most participants used the AR interface while walking, looking at the screen while navigating to the targets. Typically, when they seemed lost, they stopped and tried to re-orient themselves. Participants were also often observed to lower the device (while walking) and shaking or switching the device between hands. This was generally due to the need to relieve the fatigue resulting from holding up the device in front of them for a long time.

Combination interface

The condition that allowed users to switch between the AR and Map interfaces was rated by the participants as the most helpful in finding the targets. Many participants employed a strategy of using the Map interface for getting an initial overview of the surroundings and planning their path, switching to AR when they were closer to the target. One participant observed, “I used the map at the beginning to understand where the buildings were and the

AR between each point." Another participant noted, "I found it easier when the target was further away to look at it in the map view which allowed me to see where I was in relation to the buildings and landmarks on the map. When I got closer, I found it easier to use the AR view because that way, you can hold the phone and see where the target actually is, which gives a bit more accuracy."

However, this is was not universal and one participant preferred a reverse strategy: "AR might help when starting the task to orientate oneself and then, given that information, use the map to reach the point of interest."

User Experience

Several user comments related to overall usability issues. Although GPS accuracy and compass input issues had an effect on the user experience in all conditions, they were more pronounced in the AR interface. The correct placement and real-time tracking of the virtual objects in the real world environment rely heavily on sensor inputs and noisy sensor data leads to visual jitters: "The least helpful was the shakiness because you had to really stop and let it calm down."

Screen brightness and legibility under direct sunlight was another issue: "Just sunlight on the screen was the biggest issue which was a real pain." Many participants looked for shade in order to better see the screen content.

Gender Differences Although we did not find any overall systematic differences in user comments between the male and female participants, we observed certain differences in navigation behavior and interface usage.

Route planning was more pronounced with male participants. Female participants followed a more *ad hoc* strategy and started walking toward the next POI once they established their heading. The AR interface seemed to work well for a strategy that involved less planning and more direct target navigation behavior. Many female participants commented on making extensive use of the radar view in the AR interface. One female participant said "Overall, no major problems, just that I can't read maps." Another female participant observed, "With the map, you had to figure out where you were in relation to the map, whereas the AR mode was more based on your surroundings." In one extreme case, after having planned his route for a couple of minutes, one male participant went as far as stowing the phone in his pocket for most of the traversal, using the phone again only after getting much closer to the target.

4.6 Discussion

This study set out to establish a baseline measurement of the performance differences between map-based and AR-based pedestrian navigation tools. We had expected that AR would yield faster time-on-task performance but our results were inconclusive. In this section, we look at some of the possible relevant factors as well as interesting insights we were able to gain from the data we collected.

Discussion on Environmental Factors

An exploratory look at the different types of paths revealed some interesting results. The AR interface was found to take longer on the path that had several features that blocked a direct route to the target location. Path C in our experiment had a number of dead ends that were difficult to spot from the AR view. Several participants using the AR interface had to backtrack once they found that the route they rook was blocked by a building, a stream or other obstruction. The participants also commented on this issue and felt the lack of overview and route planning options were significant drawbacks with the AR interface. In order to show if a route or direct line of sight to a target is obstructed or not, the system would need detailed information about the environment (e.g., a detailed enough 3D model of the environment). While this may be available in the future, it is currently not widely available for use in AR systems.

Although the AR interface may result in undesired excursions off the route that are ultimately blocked, it may also reveal shorter routes between two locations that are not obvious from a top-down map or satellite view. For example, in our case, there were routes covered with tree foliage and it was not clear whether there was a way through. Archways, underground passages, etc., may exhibit similar properties. Map users, in this case, took routes that had an associated clear path in the map view which were no necessarily the shortest. Maps showing a more abstract and simplified picture may produce different navigation behavior. The option presented by the AR interface seemed enough to encourage participants to choose the route. Although the same real world information was present for map users, the lack of cartographic indicators on the provided maps was enough to dissuade users from choosing the potentially more efficient route. Whether a route was, in fact, actually present was similarly obvious—or non-obvious—to both the map and AR users since the map gave no indication that there was a path and the AR interface did not remove real world obstructions to reveal potential throughways. This may indicate that the AR cue may have a disproportionate effect on boosting exploratory confidence in users while the lack of route information on maps may inhibit the same potential to explore possible routes that may be more efficient.

Discussion on Interface Preferences

Participants indicated a clear preference for the Combination interface that allowed them to switch between the Map and AR interfaces at any time. Some participants used both interfaces in order to employ a strategy wherein an overview was used through the Map interface to first establish an understanding of the context of where they were in relation to certain landmarks before proceeding to plan their route strategy. The AR view was used when the participants were closer to the target to provide a more focused first person view directly showing the target location. This agrees with previous work that used photographs to help pedestrians navigate by landmarks through instructions effectively placed in relation to the surrounding environmental visual context of the user [95].

The use of maps to begin a navigation task was not universal, however. A number of participants used the AR interface in the beginning to scan the area, get the initial direction and then used the map to get more accurate route information. These strategies fit into the typical models of navigation with orientation, maneuvering, maintaining orientation, and target recognition, where the different interface conditions are used at different stages [16].

It appears that an interface that combines a map view and an AR view serves to give the user the option of choosing either their preferred interface or developing strategies to used a combination of these interfaces to their full advantage. However, in our study, we did not find clear evidence of users consistently adopting such optimal strategies or that they always used the optimal route when using the Combination interface. This may be due to the possibility that the participants were not always able to exploit the benefits of each interface option. Some participants that used the Combination interfaces walked into dead ends while others did not choose the short cut routes even though some of the AR-only participants did in the same situation. The additional information of the Map interface that did not indicate the short cut was an option may have curtailed their assessment of the possibilities.

Our video analysis indicated that the participants looked at the screen the longest—especially while they were walking—when using Combination interface. The addition of having to manually switch interfaces obviously keeps users occupied with the interface longer. The data also suggests that, while walking, the users looked at the screen less frequently and for less time with the AR interface than with the Map interface or the Combination interface. This conflicts with findings by Mulloni et al. [58] that AR interfaces are used more often while walking. This could be partly explained by the differences in study design: the study by Mulloni et al., was done in an indoor setting where environmental concerns are presumably very different from our study, conducted in an outdoor setting. There is, however, potential agreement in how the AR interface is used since the fact that we found users generally looking at the screen less often with the AR interface seems to support the notion that this interface is primarily used to quickly check at decision points and to confirm directions.

In overall performance, the Combination interface, though preferred, did not out-perform either of the other two interfaces. In terms of performance, it did not seem , to a certain extent, that the Combination interface offered the "best of both worlds" or that the participants were not always able to use both interfaces to their full potential. This seems to align with observations that users tend to like having options even if they never exercise the options available [62]. Further, our findings seems to agree with earlier research that performance may not be the best measure of a tools appeal to users [2].

Although our findings were not as we had expected, the fundamental differences in the nature of the navigation interfaces made it seem likely that there would be fundamental differences in usage behavior and possibly also performance differences. Our results indicated that no significant performance differences existed between the interfaces. One possibility is that our experimental design failed to isolate the performance factor sufficiently, allowing the noise of other factors to hide actual performance. For example, the GPS-based AR interface was often too unstable to provide instant information and users needed to wait for the tracking of the rendered graphics to settle on its correct position before seeing what the navigation cue was indicating. Also, the aerial maps may have been sufficiently different from the standard cartographic maps that participants are familiar with, so that its usage was almost as novel as the AR interface.

Our study was, to the best of our knowledge, the first study to compare the performance of map and AR navigation interfaces. However, unbeknownst to us, a group in Vienna, Austria, was in the process of conducting a similar experiment at the same time. They also compared three conditions in a within-subjects design: map, AR, and turn-by-turn voice-based instructions [74]. Their maps were standard cartographic maps and the environment was an urban one with streets rather than a campus area with footpaths. Their results were similar: no significant differences were detected between the interfaces.

Gender Differences

Male participants produced better overall performance results than female participants which replicates findings in the literature on spatial navigation [12] [43] [92]. While performance of male participants with both the Map interface and Combination interfaces was better than with the AR interface, there was no difference in task completion times between genders for the AR interface.

Studies have shown that men rely more on survey knowledge while women rely more on landmark knowledge [12]. Consequently, men have generally performed better in navigation studies using maps. This might explain why female participants performed better with the AR interface than with the other interfaces: AR is essentially a landmark-based tool and not only would this factor favor the female participants but the lack of a survey-based tool may handicap male participants. Interestingly, the female participants did not rate the AR interface more favorably than the other interfaces nor did they use the AR interface significantly more often than the male participants in the Combination interfaces.

4.7 Conclusion

In this chapter we have explored AR navigation compared to 2D map-based navigation. We did not find any statistically significant differences in the performance of participants in our study between interfaces, but there were behavioural and subjective differences.

Since the time expended to reach a destination is similar between different tools, it appears that we need to refine our experiment to extract what is evidently a small effect potentially lost in the noise (of GPS inaccuracies or other environmental factors) or that we need to turn to other possible measures that would allow us to compare the effectiveness of pedestrian navigation tools. Although time-on-task performance is a reasonable measure of a pedestrian navigation tool, it is not clear if pedestrians are as concerned about performance on a practical level as, say, vehicular drivers would be. Pedestrians may freely wander on a whim, using navigation tools whenever they felt lost but without the feeling the need to follow the tool to the original destination.

Based upon the experiment described in this chapter, we noted that users stated their preference of having multiple options available to them even if they do not exercise the options. We need to better understand the practical aspects of this perspective and how it affects actual usage of pedestrian navigation tools. Given equally effective tools, performance-wise, users will presumably prefer the tool that they perceive as being more appealing or easier to use. The lesser degree of cognitive effort needed to use tools that a user finds to be easier to use may contribute in a similar manner to the formation of cognitive maps. It is the manifestation of such preferences for certain pedestrian navigation tools over others that we now wish to better understand. This is the work we describe in the next chapter of this dissertation.

5

Nav2: Perception and Preferences for AR and Other Pedestrian Navigation Tools

As we saw in the previous chapter, the differences in performance between AR-based and map-based mobile pedestrian navigation tools were statistically insignificant. This finding was unexpected and the causes for it may be divided broadly into objective and subjective possibilities. We will visit the objective possibilities in the next chapter; here, we examine the possible subjective causes rooted from a user's perspective. We designate this study as Nav2 and it was designed to address research goals RG3 and RG4 (see Section 3.2) and the associated hypotheses, H3 and H4 (see Section 3.3).

5.1 Introduction

Fulfilling the navigational needs of pedestrians is challenging, in part because the appropriate guidance information can literally change with every step. While automobile drivers can generally be relied upon to follow the turn-by-turn directions of an in-car GPS system, pedestrians are far less predictable given the freedom they have to ignore instructions due to preferences for efficiency, aesthetics, safety, or any number of other factors [54]. This greater latitude is matched by the wide variety of navigation tools continually being introduced to the market, from traditional maps with dynamic enhancements—such as a You-are-Here indicator—to 3D models of urban environments to AR tools.

The desire to create specialized interfaces that target particular situations is a sensible one, but the sheer diversity of options can serve to overwhelm and confuse users. It is not clear how a determination can best be made as to which tool is, in fact, the most suitable for a given situation.

Differences in individual perception and preferences will result in different assessments of a tool's appeal and, as a result, in how much a tool is actually used. In the study described in this chapter, users are given a set of tools to choose from in order to complete the assigned navigation tasks. We hope to gain insights into how users choose between different pedestrian navigation tools and, based upon the data collected, we attempt to classify users based upon usage behavior so that navigation tools can be designed for more targeted groups of users.

5.2 Background

The growing variety of mobile pedestrian navigation tools is making it increasingly difficult to choose the best tool for a given situation. Instead of choosing a favorite navigation tool and using it for all navigational needs, multiple interfaces—rather than a one-size-fits-all solution—may be appropriate for pedestrian navigation guidance since different navigation interfaces may be better suited for different situations [1][73]. Consequently, it may be that providing a combination of multiple interfaces may be a sensible way to allow a user to navigate more efficiently and effectively. However, many navigation studies focus on particular interfaces, typically testing the separate interfaces independently rather than as a group [73]. As such, it may not reflect how users would choose between different tools if presented with the option to do so throughout a navigation task. Several studies comparing new interfaces—3D maps [72][91][41], photographic-based navigation tools [28], and AR [74]—did not provide participants with the means to freely switch between interfaces. In these studies, participants expressed interest in having the option of selecting from multiple tools. Without actually providing them with an option to switch between interfaces, it was not clear if their expressed interest would have been supported by real world usage behavior leading to more efficient navigation.

As noted in the Nav1 study described in Chapter 4, the combination mode (with both the map-based and AR-based interfaces available) was preferred by the participants but did not deliver the most efficient performance in terms of task completion time. In post-test interviews, some participants stated a preference for one tool over the other in the initial or end phases of the navigation task but it was not clear if the comments were based upon actual usage strategy employed or perceptions of what they thought were appropriate strategies to take. A stated preference for multiple tools, in and of itself, does not necessarily imply an efficient use of the various tools in a manner that would optimize the navigation task. Rather, the desire for more tools may actually be due to the perception that users may feel more secure when they feel they have a greater number of options, even if the options are not necessarily exercised [62].

The situation where users do not exercise the optimal options available is not a necessarily a simple consequence of a system having too many options for a user to consider. Instead, it may be due to such factors as *loss aversion*, which addresses the large disparity and non-linear relationship observed in people's reluctance to give up what they have in exchange for potential gains [90]. Well understood as a phenomenon in behavioral economics, we apply the concept of loss aversion to interface usage to refer to users who may prefer to passively retain a tool currently in use rather than to pro-actively switch away from it for an alternative that may or may not be as effective as the current tool. Clearly, the subject of user preferences is a complex one with many factors involved. While performance data can be collected by simply measuring performance results, the complicated nature of user preferences will require a greater pool of data examined in a more sophisticated manner.

Prior work has scrutinized usage patterns based upon a number of observable factors from walking style to technology usage patterns to cognitive loads incurred by various interfaces. Using spatio-temporal measures such as average velocity and frequency of stops, pedestrians actively shopping were categorized into groups based on observed preferences with labels such as utilitarian, hedonistic, convenient, swift, and discerning [52]. Pedestrians were also classified by tracking eye movement and interpreting the glance patterns in order to deduce three types of usage behavior in navigation tasks: Constant Support and

Information, Independent and Attentive, and Least Effort and Inattentive [98]. Offering users the ability to choose between a map-based navigation tool and a text-based route directions tool in a virtual setting, a cluster analysis conducted over recorded usage choice yielded three types of users: those that preferred text-based route directions, those that used maps heavily, and those that used maps less frequently [46].

In summary, the growth of mobile pedestrian navigation aides has made the potential of using multiple tools for one navigation task a desirable possibility but comparable studies are largely based on single interface conditions. Further, given the complexities of individual differences, attempts to better understand how users may actually use available tools generally seek to create classifications of user types. With this in mind and given our interest in better understanding how, when, and in what situations users may choose to use AR, we describe the Nav2 study we undertook to gain insights into user preferences when presented with a number of pedestrian navigation interfaces, including an AR-based tool.

5.2.1 Objectives

We have two objectives in this study: (1) to better understand how preferences for a navigation tool may be depend on how much a navigation task has already been completed and (2) to categorize user preferences for navigational tool types based upon usage behavior.

Phase dependent preferences

We wish to investigate if navigation tool choice is dependent on the phase of a navigation task. That is, would users prefer a certain type of tool in the early stages of navigation but prefer a different tool in the latter stages? Adaptive interfaces have been created to present information differently depending on user proximity to locations where navigation information could be updated appropriately [58]. In the same manner that interfaces may change to accommodate users based upon their location, we hypothesize that users may favor different interfaces for different portions of a navigation task. Specifically, we believe that, within a single navigation task, a user would exhibit preferences for one tool during one phase of the navigation and another tool during another phase. For example, users may wish to have a broad overview when beginning a navigation task but then switch to a more directional tool when nearing the destination.

Classifying user preferences

We would like to see how the choice of navigation tools may reflect upon how individual users may have fundamental differences in how they use such tools. In particular, we would like to apply a different methodology in identifying possible categorizations of user so that we can build up the body of work in this area, which is generally comprised of smaller scaled studies, given the resource-intensive nature of pedestrian navigation studies.

5.3 Methodology

In order to better understand some of the factors that may affect usage of navigation tools, we designed an experiment to study how users behaved when provided with multiple navigation interfaces.

5.3.1 Interface Conditions

For the collection of interfaces, we selected pedestrian navigation tools that form a representative set of such applications currently deployed on mobile devices. Pedestrian navigation tools can be broadly divided into two types: *directional tools* and *survey tools*. Directional tools point to the destination regardless of obstructions (e.g., buildings) that may be in the way of reaching the destination directly. Survey tools offer an area overview which allows route planning.

We created an iPhone application that included both types of tools, offering five different interfaces:

- **North-up map:** A standard cartographic map displaying the user location and the destination of the navigational task and oriented so that north was always aligned with the top of the screen (see Figure 5.1(a))
- **Forward-up map:** A standard cartographic map displaying the user location and the destination of the navigational task and oriented so that the top of the map is

always aligned with the direction the device is pointed (see Figure 5.1(d))

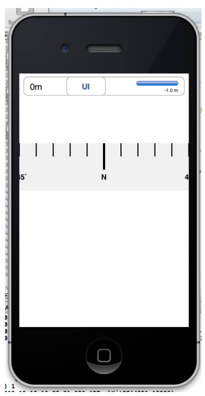
- **Linear Compass:** A ruler-like linear strip that subtended a 90 degree angle and which indicated the position of the destination if it is within the subtended angle or, the direction to turn in order to bring the destination into view (see Figure 5.1(b))
- **AR:** A video feed of real world through the device camera with computer generated graphics overlaid, as a three-dimensional cube, in the position of the destination of the navigational task (see Figure 5.1(e))
- **Radar:** A traditional radar metaphor showing the user at the center and the destination of the navigational task relative to the user within a circular area using a logarithmic scale radially to maintain its visibility regardless of distance (see Figure 5.1(c))

The distance to the destination and GPS accuracy are shown in the upper left hand corner in each of the interfaces.

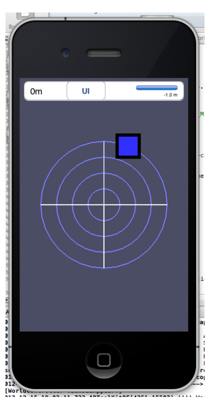
When initially presented to the user, the application displayed a menu with buttons for choosing one of the five interfaces described above. The menu could be activated at any time should the user wish to switch between interfaces. To minimize loss aversion, we built a mechanism that forced users to choose a new (or re-choose the existing) interface. This was accomplished by including a timeout mechanism that forced users to periodically choose from the various interfaces. Whichever interface the user chose was immediately invoked and was made the active navigation interface for 20 seconds before the menu was displayed again, forcing the user to choose again.

The user may choose to ignore the menu and to not use any of the interfaces or may choose to select one of the menu items–including the previously used interface–in order to use one of the navigational tools for another 20 seconds. If the user wished to switch interfaces before 20 seconds had transpired, a button that returned to the menu was shown in each of the interfaces. The button enabled the participant to abort out of the interface before the timeout thus serving as an immediate return option. Due to the potentially disruptive nature of forcing users to periodically consider their chosen inteface, we tested its effect in pilot tests but received no negative feedback.

(a) North-up map

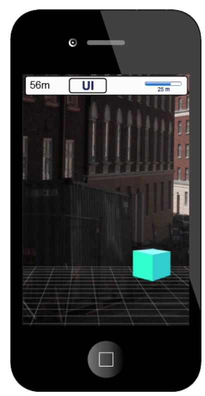


(b) Compass

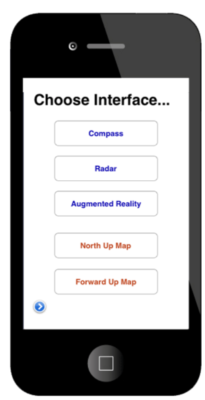


(c) Radar

(d) Forward-up map



(e) AR



(f) Menu

Figure 5.1: The navigation intefaces and menu

5.3.2 Environment

The study was conducted in Helsinki, Finland[1] in the neighborhood of Punavouri, as shown in Figure 5.2(a). Punavouri was chosen because it satisfied a number of criteria including urban surroundings, manageable size, non-trivial layout, good quality GPS signal, interesting landmarks, and minimal street traffic. We targeted visitors to the city who would have minimal experience with the city and so we wanted to ensure some interesting sites that would help in the recruitment process.

5.3.3 Procedure

After a brief introduction and a pre-test demographic questionnaire (see Appendix B) which included questions about their proficiency with maps and technology, each participant underwent a training phase. This used a modified form of the software technology where the timeout was disabled and only one interface was available at a time. The training path was approximately 500 meters long and was divided into five segment pairs, each of which corresponded to one of the five interfaces. The participant was shown how to use the interface and then used it to navigate to the destination. When the participant was within 15 meters of the destination the iPhone vibrated and displayed an alert indicating that the destination had been successfully reached. The relatively large range of 15 meters was chosen after some pilot tests revealed locations that required compensation for signal disruptions in the neighborhood.

After completing the first segment of the segment pair, the user continued to the second destination with the same interface. Upon arrival at the second destination for the interface, the participant completed a usability questionnaire and a NASA TLX survey, a subjective workload rating procedure based upon mental, physical, and other perceived user demands. This was repeated four more times, once for each of the remaining interfaces. The area for the Interface Path used the training is shown in Figure 5.2(b).

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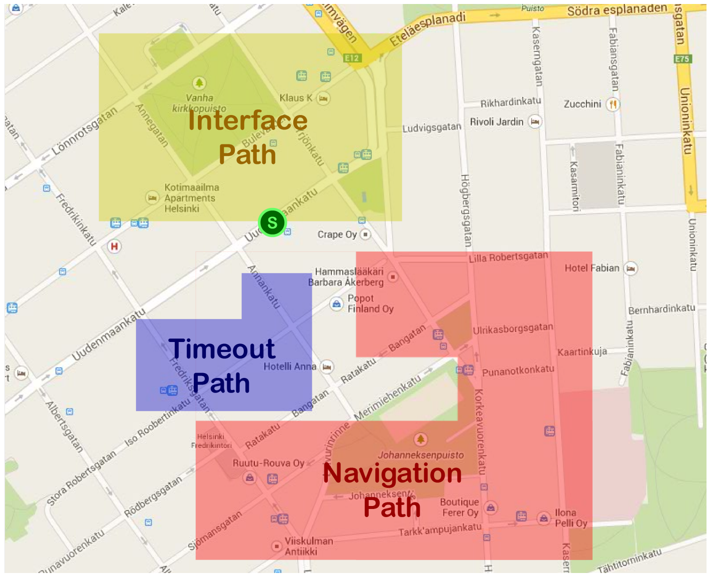
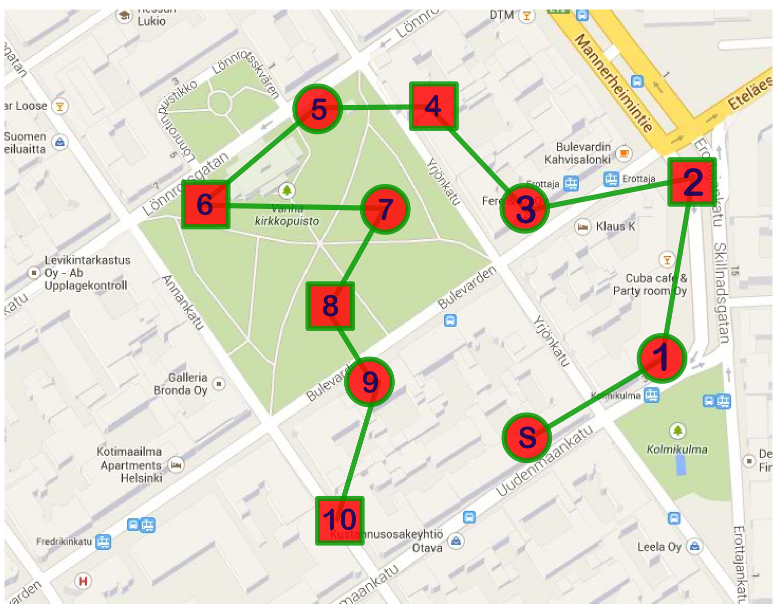
[1]Because of the earthquakes of Sepember 2010 and February 2011, our original experimental design, which was based in Christchurch, New Zealand, had to be abandoned as the city was strictly closed off to traffic, pedestrian as well as vehicular. A grant to continue the study with a partner institution, Aalto University in Finland, was secured through MARCUS and the experimental path was re-designed in Helsinki, Finland.

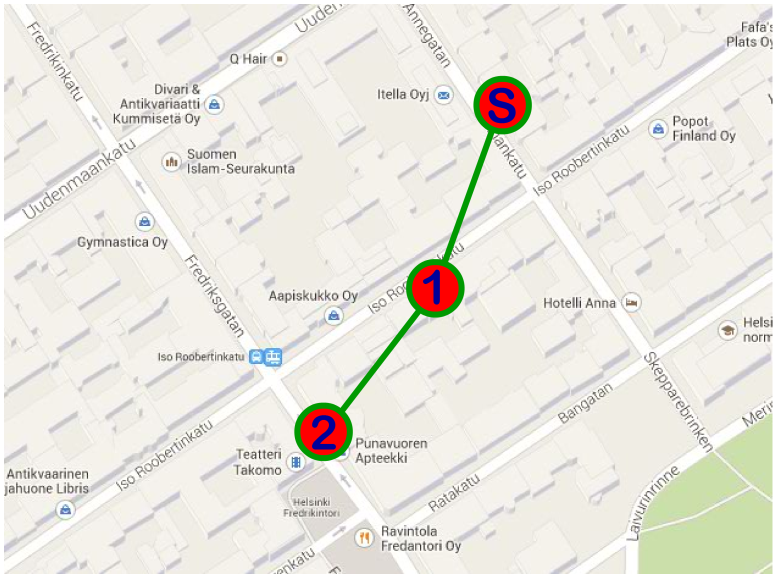


(a) The neighborhood in Helsinki within which the study was conducted.

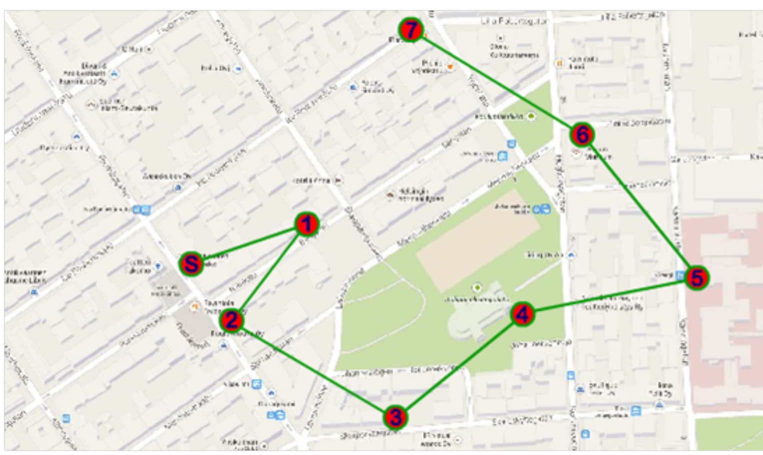


(b) Interface Path: The path participants took to train with the five interfaces. Each interface had two destinations, the second of which included the completion of a usability and workload survey.

Figure 5.2: (a) The overall neighboorhood for the study and (b) the training path



(a) Testing Path: The path participants took to familiarize with the multi-interface tool and the timeout mechanism.



(b) Trial Path: The path participants took for the experimental trials. The path is divided into seven segments and the participant is given a questionnaire to complete at each the end of each segment.

Figure 5.3: (a) The testing path and (b) the trial path.

A short testing phase followed so that the participant could have the opportunity to become familiar with the imposed time limit and the navigational tool selection menu. The testing path was a short distance away from the end of the training phase and was approximately 200 meters in length. It included two destination points and two turns. The participant was encouraged to try the various interfaces as well as experience how the system replaced the interface with a menu when it timed out after twenty seconds. This is shown in Figure 5.3(a).

The experiment proper began at the location where the testing path ended and, after ensuring the participant was comfortable with the application—they were asked if they would like more testing time; none of the participants requested it—the participant began by selecting an interface to navigate to the first destination of the experimental trial. Seven such navigation tasks were undertaken, with each new task following where the previous task ended. At the end of each navigation task, participants were asked to rate their spatial sense in the beginning, middle, and end sections of the just completed segment on a 7-point scale (see Appendix B for the questionnaire administered). After completing the experimental trial, participants were given a questionnaire with the opportunity to write comments as well as to rank the interfaces in terms of usefulness for each of the three intra-segment sections: beginning, middle, end (see Appendix B for the post-test questionnaire). Each segment ranged from approximately 75 meters to approximately 300 meters although participants who deviated from the optimal path were not corrected and so could potentially wander much further afield. At each destination, the participant completed a short questionnaire and, after the last destination, the participant was given a post-test questionnaire. On average, participants spent 19 minutes traveling a distance of 1.6 km over the entire path. The area with the designated waypoints is shown in Figure 5.3(b).

The three paths were designed to minimize the amount of walking between paths, as shown in Figure 5.2(a). In total distance in the optimal traversal was approximately 2.6 km.

5.4 Results and Analysis

In this section, we present the results from the study. We describe the participant pool as well as the subjective and objective data collected. We also report on the analysis of the data.

5.4.1 Participants

Thirty participants (11 female), ranging in age between 19 and 42 years (M = 27.3 years, SD = 6.18) completed the user study. They were told to expect a substantial amount of outdoor walking within an urban environment for the study, which lasted between 1.5 and 2 hours. Self-assessed proficiency on a seven-point scale (1=low, 7=high) with technology was above average (M=5.43, SD=1.55) as was map skills (M=5.50, SD=1.38). Participants were given a pair of movie passes in return for their time.

5.4.2 Perceived Usability

The results from the 7-point Likert scale (1=Disagree, 7=Agree) questions for perceived usability (see Appendix B) given after the interface training phase are shown in Table 5.1. The table also shows the Omnibus ANOVA applied over the data for perceived usability. (It should be noted that, although the analysis of Likert scale data is often by non-parametric means, an ANOVA test was chosen based on the strong arguments made by Norman on the appropriateness of applying ANOVA test for Likert results over Kruskal-Wallis and other non-parametric tools [63].)

	Mean	Std Dev	F(4,144)	p
Easy to use	5.91	.85	4.76	$< .01$
Usefulness	5.94	.79	1.99	.099
Intuitive	5.65	.87	3.71	$< .01$
Goal is Obvious	5.48	1.01	35.89	$< .001$

Table 5.1: Results for Omnibus ANOVA from user assessment of interfaces

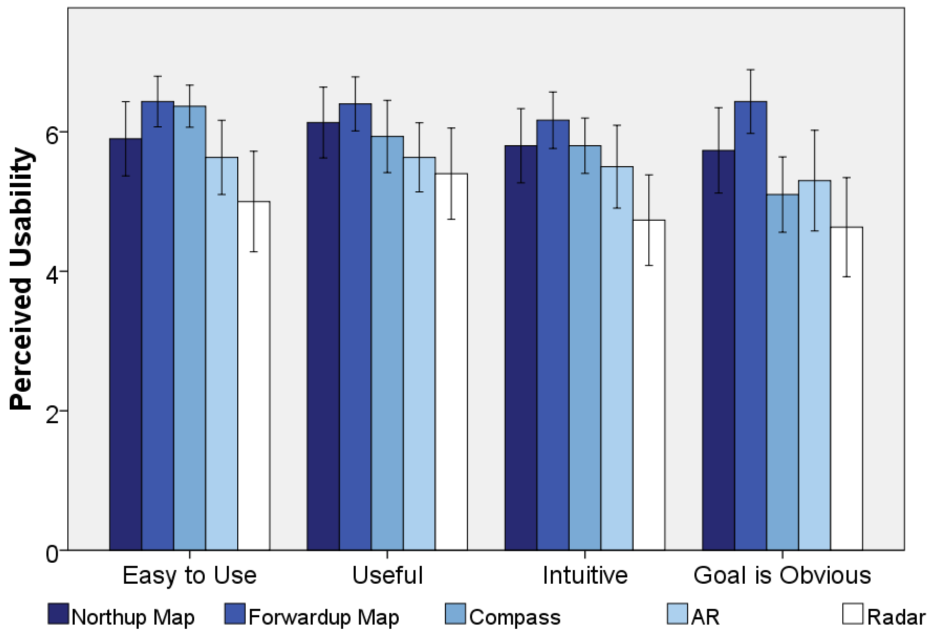


Figure 5.4: Usability Survey Results

Post hoc Bonferroni analyses were used to identify the significant differences detected in the Omnibus ANOVA. For ease-of-use, both the Compass and the Forward-up Map were perceived as significantly easier to use than the Radar interface ($p < .01$). The North-up Map as well as Compass and Forward-up Map interfaces were all perceived to be significantly more intuitive than the Radar interface ($p < .05$). The Forward-up Map was seen to be significantly more obvious in showing the goal than both the Compass interface ($p < .05$) and the Radar interface ($p < .001$).

5.4.3 Perceived Workload Demand

Figure 5.5 shows the scores for the perceived workload demand based upon an average of the NASA-TLX items for each person for each tool. High levels of internal consistency (Cronbach's $\alpha > .89$) were found for all the interfaces except the Radar (Cronbach's $\alpha = .59$).

A repeated-measure ANOVA determined that there were statistically different perceived workloads depending on the interface used, $F(2.97, 83.013) = 6.86, p < .001$. Bonfer-

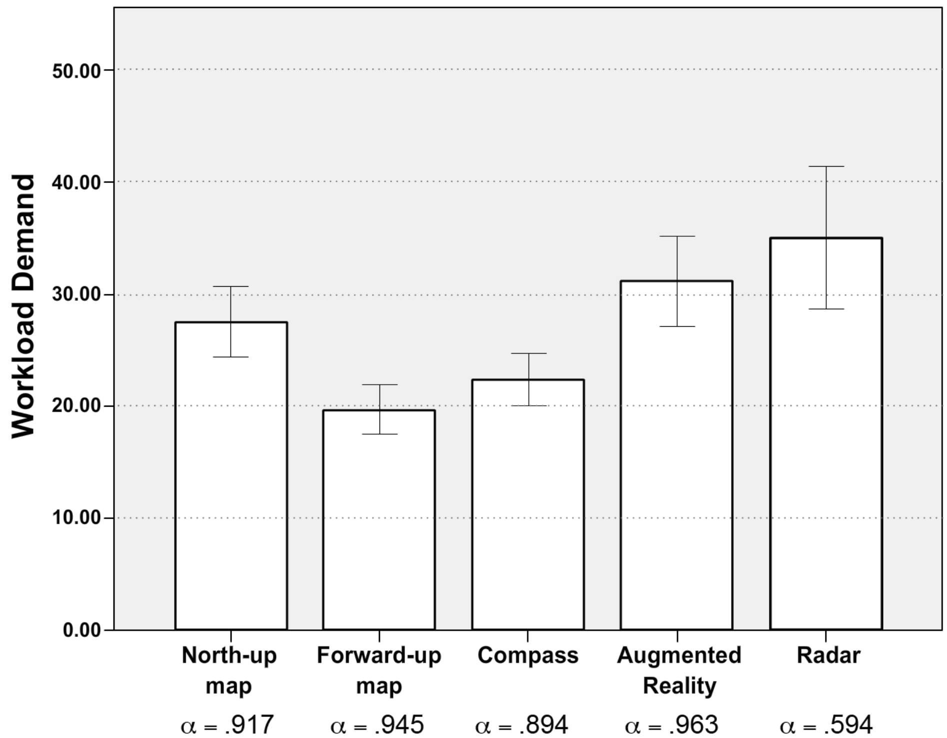


Figure 5.5: Perceived Workload Demand with Cronbach's α

roni post hoc analysis indicated that the Compass interface ($M = 22.41, SD = 2.35$) and Forward-up map ($M = 19.72, SD = 2.14$) had significantly lower perceived workload demand than both AR ($M = 31.17, SD = 4.11$) and the Radar interface ($M = 30.97, SD = 3.76$).

5.4.4 Interface Usage

Interface usage time was logged during the experimental trials. Participants generally referenced the device periodically rather than monitored it continuously so the automatic timeout removing the interface may go unnoticed. We chose to interpret the time where the device did not display any navigation tool as an indication that the user was still relying upon the most recent interface. In other words, the information given by the most recent navigation interface was still being actively used without a need for further information.

Consequently, we combine the time the interface is actively displayed (active time) with the time the menu is displayed immediately after the timeout has occurred for the interface (passive time) and used this combined time for our analysis in usage time and traversal speed.

Figure 5.6 shows the percentage of time each interface was used over the seven segments. Averaged across users, it can be seen that the Forward-up map starts with the greatest percent of usage in the first segment ($M = 37.7\%, SD = 5.3\%$) while the Radar starts with the least usage ($M = 8.3\%, SD = 2.4\%$). Forward-up map usage generally increased over the segments, reaching a maximum at the last segment ($M = 59.2\%, SD = 5.8\%$). Usage of other interfaces all drop, with AR dropping most substantially (from $M = 18.1\%, SD = 4.1\%$ to $M = 6.5\%, SD = 1.9\%$).

In order to analyze the relationship between interface choice and interface usage time, a pair-wise correlation analyses were performed between segments for both interface usage time and for tool selection. As shown in Figure 5.7(a), the Spearman's Rho correlation coefficients for usage time between consecutive segments grew from a medium effect ($r = .38$) to a strong effect ($r = .72$) to the $p < .001$ level. The correlation coefficients were lower for interface selection, ranging from a small effect ($r = .11$) to a large effect ($r = .52$), to a $p < .001$ level. This indicates that participants settled into using particular sets of interfaces over time.

Given the disproportionate preference for Forward-up map, as can be seen in Figure 5.6, the correlation shown in Figure 5.7(a) may be heavily biased to how that one particular interface is used. We therefore repeated the analysis without the Forward-up map data to see if any learning effects could be detected over the remaining interfaces.

As can be seen in Figure 5.7(b), a learning effect persisted even with the Forward-up map interface removed. The Spearman's Rho correlation coefficients for usage time were smaller across all the segment pairs but the correlation between segments still ranged from a medium effect ($r = .25$) growing to a large effect ($r = .59$), all the effects being significant to a $p < .001$ level. For interface selection, a growing correlation was still evident, but on a diminished scale with a small effect between segments 3 and 4 ($r = .15$) growing steadily to a medium effect for the last segments ($r = .39$) with significance to the $p < .001$ level.

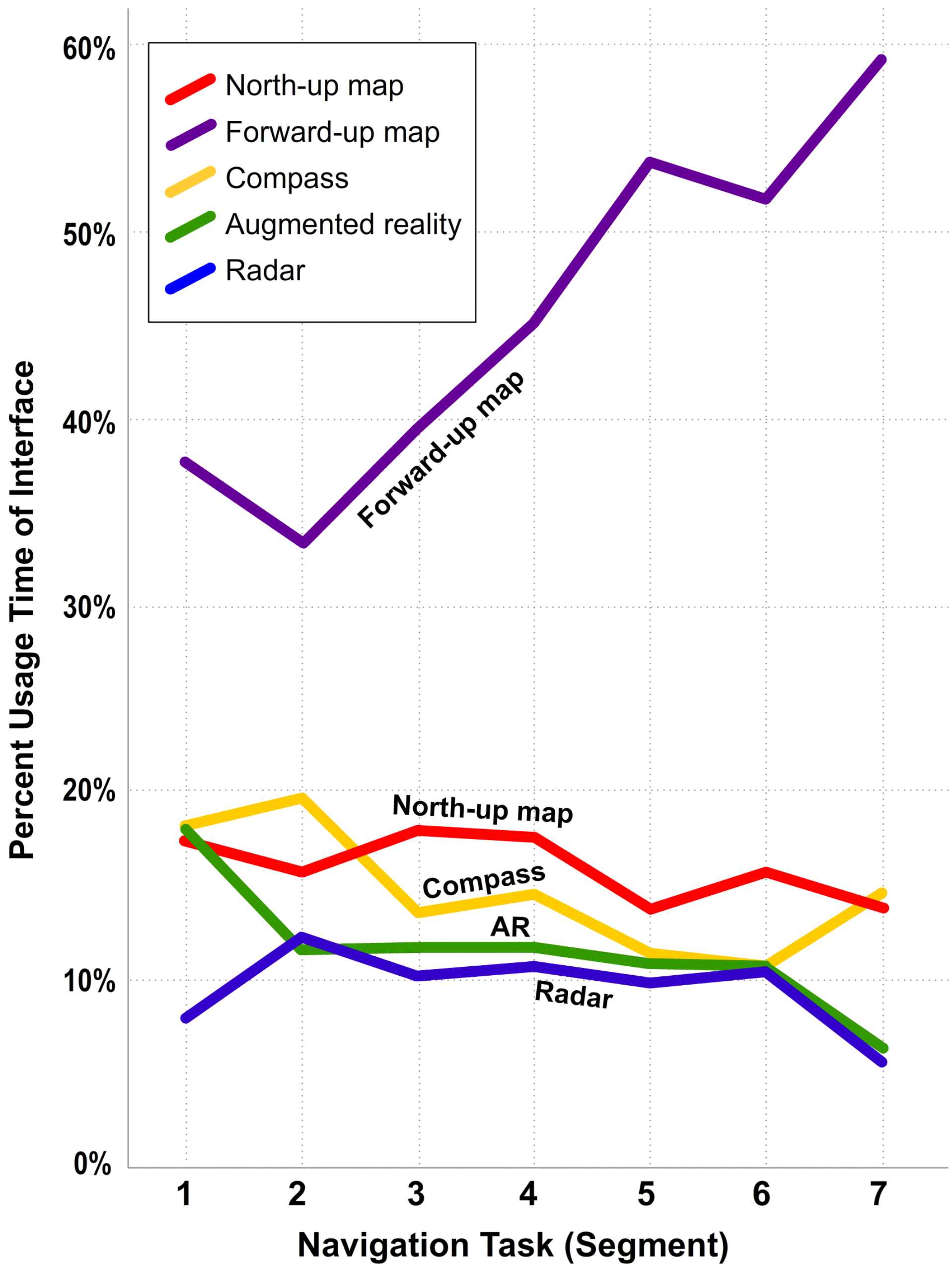
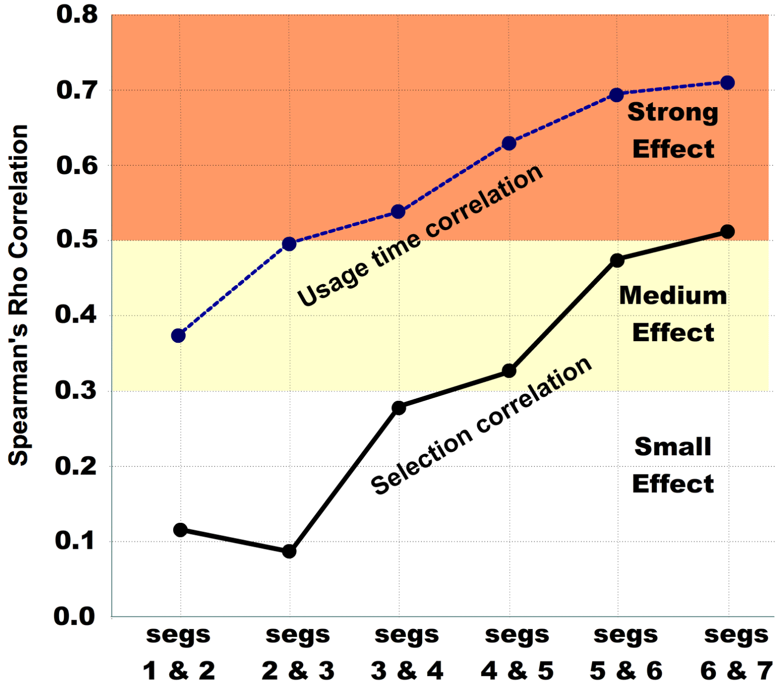
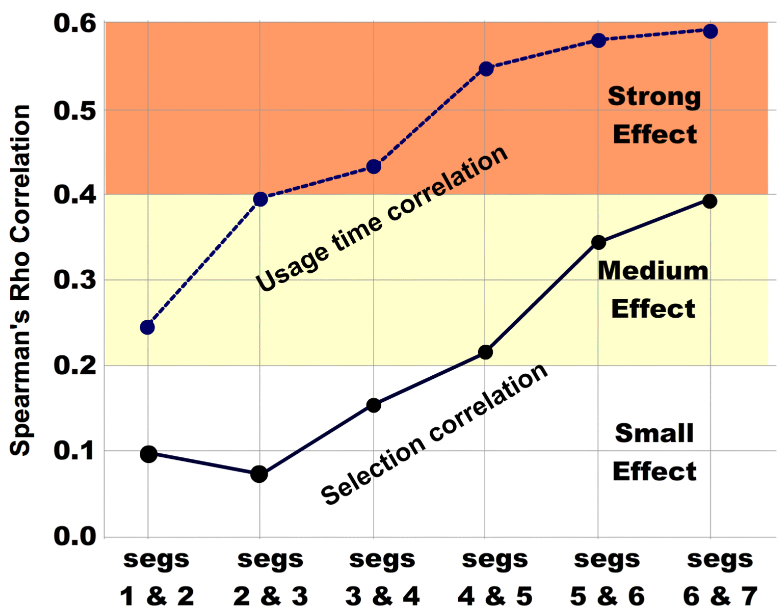


Figure 5.6: Percent time spent using the various interfaces



(a) Spearman's Rho correlation calculated over the seven segments.



(b) Spearman's Rho correlation calculated over the seven segments without the Forward-up map.

Figure 5.7: Spearman's Rho correlation calculated over the seven segments.

No significant correlations were detected between the first three segments.

5.4.5 Traversal Speed

Traffic conditions did not interfere with the participants but stops were sometimes made in order to interpret the navigation tools. The stops were therefore considered a consequence of the tool itself and part of the speed calculation, which was determined by dividing the total distance traversed (in meters) by the time transpired (in seconds) for each interface. The average speed was then collapsed over the seven segments and the thirty participants. An ANOVA showed that the interface used had a significant effect on the traversal speed, $F(4, 128) = 3.00, p < .05$. A post hoc Bonferroni analysis indicated a significant difference in speed between the Compass ($M = 1.49m/s, SD = .21$) and the AR ($M = 1.22, SD = .49$) interfaces. This is shown in Figure 5.8. No significant differences in speed were detected between the other interface conditions.

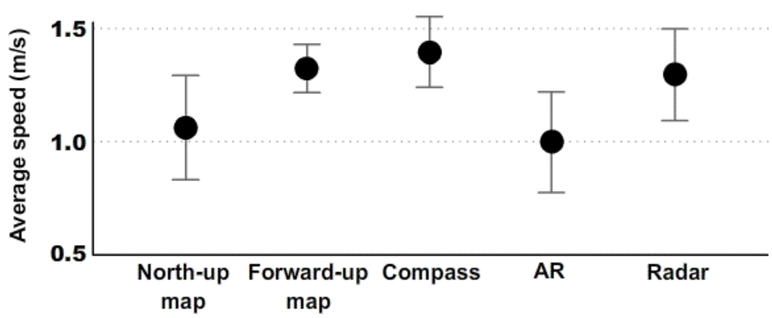


Figure 5.8: The highest average speed attained was with the use of the compass interface.

5.4.6 Navigation Phase Dependencies

The results of the spatial sense surveys completed at the end of each of the seven wayfinding tasks are shown in Figure 5.9.

Participants generally gave agreed with high ratings for feelings of where they were on a 7-point scale where 1=Completely Disagree and 7=Completely Agree ($M = 6.18, SD = 1.41$). An insignificant drop between the beginning and middle phases was followed by a

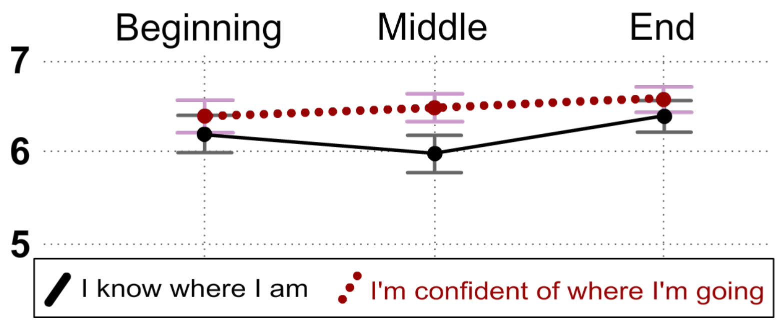


Figure 5.9: Participants had lowest sense of where they were in the middle of a navigation task but their confidence in where they were going increased.

	Beginning	Middle	End
Perceived	F N C R A	F C R N A	F A C N=R
Time used	F N C R A	F N C A R	F C N A R
Selected	FCNRA	FCANR	FCANR

Table 5.2: Perceived interface usefulness compared with actual usage time and selection (N = North-up map, F = Forward-up map, C = compass, A = AR, R = radar) for the beginning, middle, and end phases of the navigation tasks.

significant increase ($F(2, 673) = 4.350, p < .05$). Average confidence about where they were going was high throughout ($M = 6.47, SD = 1.15$).

Figure 5.10 depicts a count of the number of interface choices made for each interface and shows an increase in interface request in the middle phase corresponding to the dip in spatial perception. The selection of AR increased in the final phase while the selection of all other interfaces remained relatively constant or decreased.

The post-test rankings of interface usefulness (as described in Section 5.3.3) are given in Table 5.2, which shows the interfaces in order of perceived usefulness ranking for the beginning, middle, end phases of the navigation. These are shown along with actual time used and the number of times selected. This enables us to compare participant perception of the interfaces with the actual amount of time they used each interface as well as the actual interface selections they made within each phase.

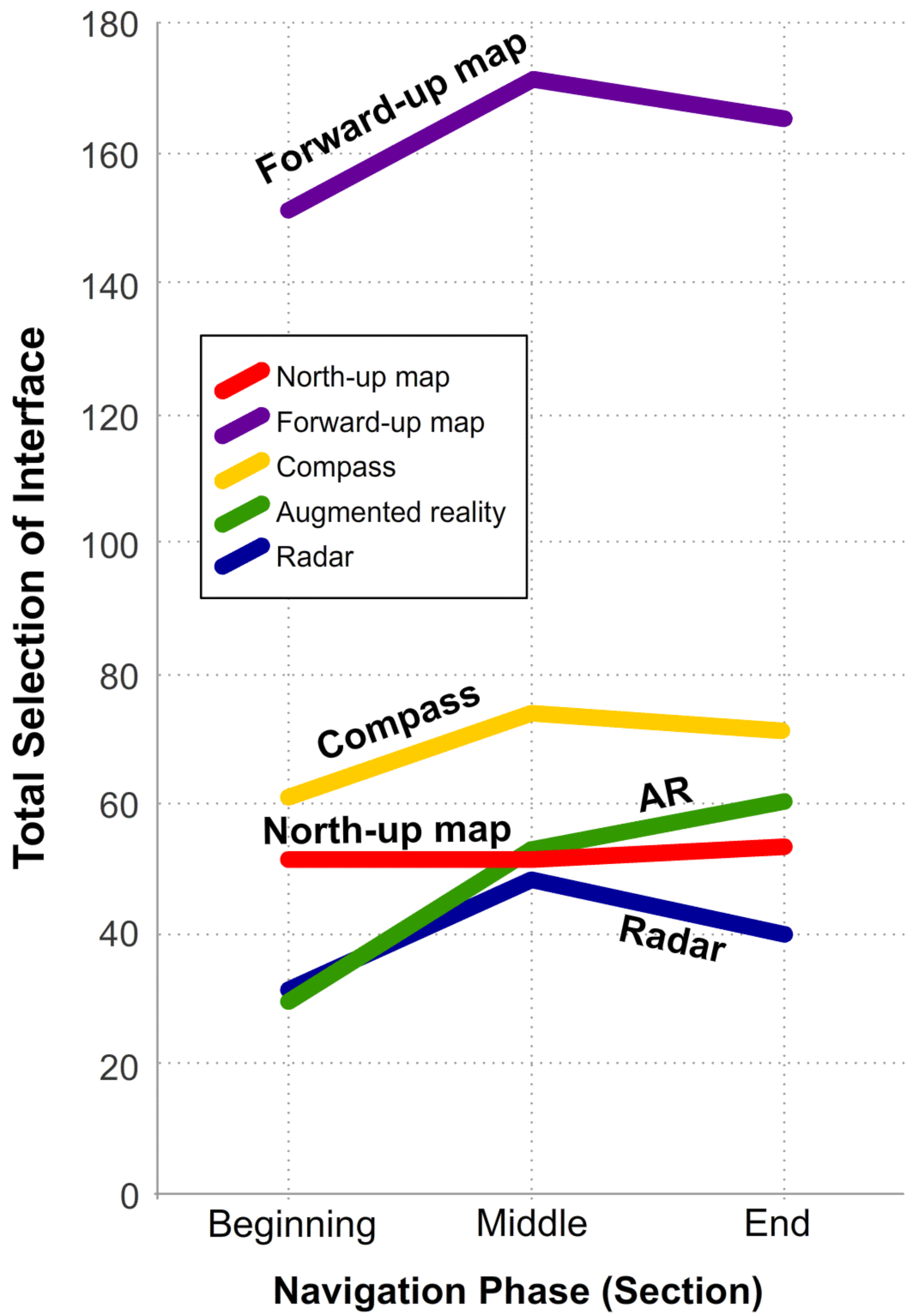


Figure 5.10: The selection of AR rose while other interfaces declined after an initial phase of navigation.

The Forward-up map interface was both most highly ranked and widely used. The compass interface was relatively consistent in perceived usefulness and actual use. The lower ranking of usage time against selection likely indicates the simple and quick nature of its information. The North-up map exhibited lower selection but greater usage time, indicating denser information and/or effort required. The radar received low rank throughout but AR was perceived to be considerably more useful at the end phase and selected more frequently in the middle and end phases.

5.5 Classification of Users

Our interest in better understanding how users may choose particular pedestrian navigation tools clearly relies upon user preferences, which may be a very individual consideration that is difficult to generalize and analyze. In an attempt to make some progress in this area, we used the data we collected in this study to create a broad categorization of users.

We classified the participants of our study by conducting a cluster analysis over the survey results as well as logs of usage data and then applying analyses of variance to identify significant differences between the clusters.

5.5.1 Cluster Analysis

We applied a hierarchical cluster analysis over data collected from the following measures:

- Self-reported map proficiency (7-point scale)
- Self-reported technology proficiency (7-point scale)
- Variety - the number of interfaces used
- Pro-activity - the number of times an interface was aborted before the timeout expired
- Consistency - the number of times the interface chosen was the same as the previous interface used
- Post-test ranking - participant rankings of the interfaces in order of preference
- Usability average - the average of interface usability questions given after the initial training

- Workload average - the average of the NASA TLX survey given after the initial training
- Selection - a count of number of times each interface was selected for use
- Active usage time - the time, in seconds, each interface was visible on the device
- Passive usage time - the time, between an interface timeout and the user activation of the next interface

Data for map proficiency, technology proficiency, variety, pro-activity, and consistency were collected on a per user basis; the remaining six variables were collected for each of the five interfaces per user. The dendrogram produced by the cluster analysis suggested a four-way partitioning, as shown in Figure 5.11. Using a K-cluster analysis we produced four clusters with membership sizes of 14, 5, 3, and 8 participants.

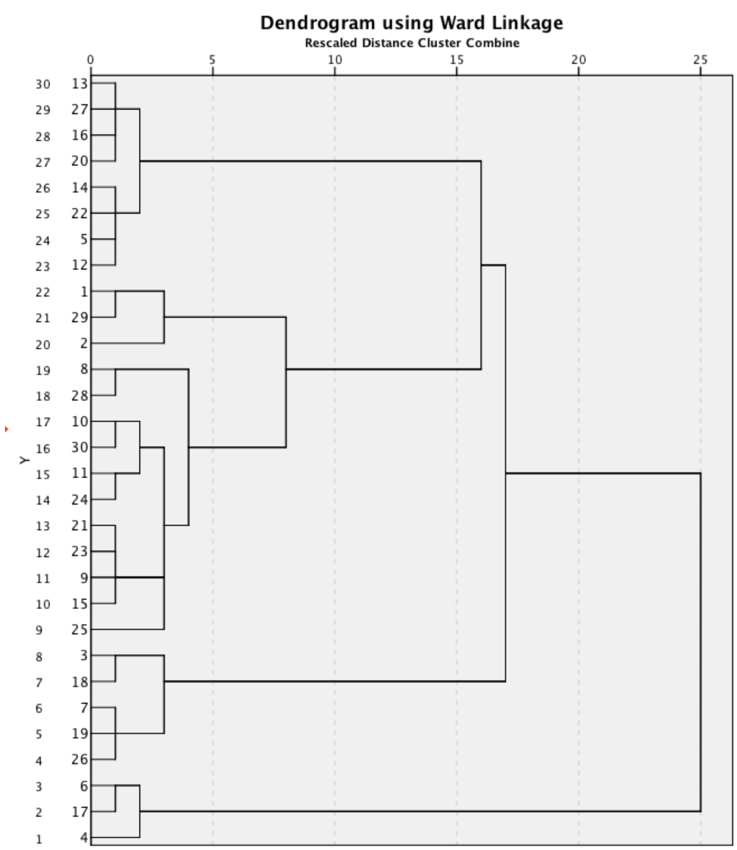


Figure 5.11: Dendrogram from the cluster analysis indicating a potential four-way partition.

Categorizing Users

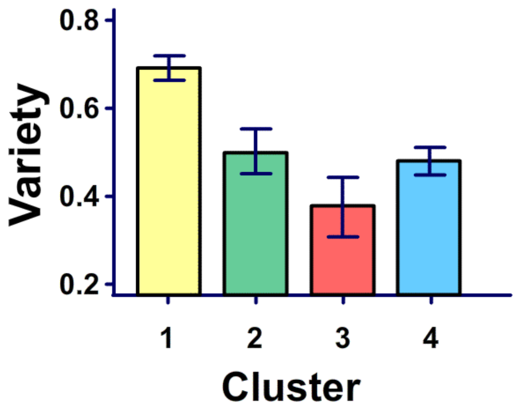
Table 5.3 summarizes the levels of distinguishing factors that yielded significant differences between clusters. To determine the significant differences given the unequal cluster sizes, we turned Lantz's argument that ANOVA are more powerful for small sample sizes while the non-parametric Kruskal-Wallis test responds "erratically [for] unequal sample sizes" [5]. Further, based on the suggestions by Quinn and Keough for small and unequal sample sizes that ANOVA tests would yield correct results when the results are highly significant (i.e. $p < .001$) [71], we were confident in our findings for Variety and Retention Ratio but conducted a Kruskal-Wallis test despite its shortcomings for the Consistency results, since the significance level was not very high, at $p = .007$; the results aligned with the ANOVA results. We examine these categories more closely in the following sections.

Cluster	Size	Variety	Consistency	Retention Ratio
1	14	High	Low	Low
2	5	Medium	High	Low
3	3	Low	High	High
4	8	Medium	Low	High

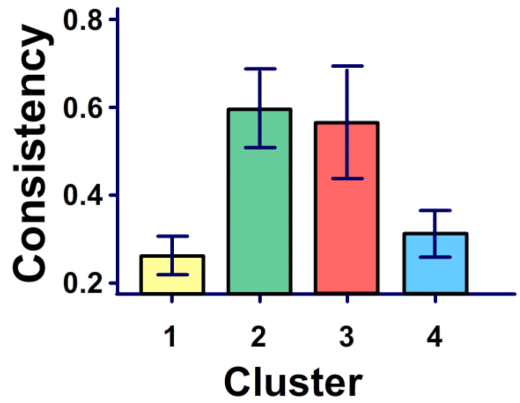
Table 5.3: Amount of variety, constituency, and retention ratio in the four identified clusters.

Variety and Consistency

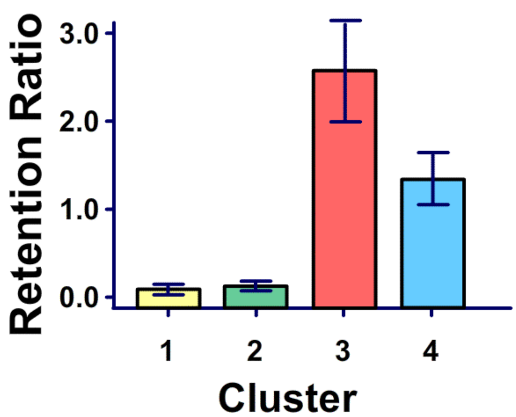
Figure 5.12(a) shows the average percentage of different interfaces selected by the participants of the identified clusters. With respect to *Variety*—the number of different interfaces selected—an omnibus ANOVA detected significant differences existed between the clusters ($F(3, 26) = 13.64, p < .001$). A Bonferroni post hoc analysis indicated that Cluster 1 had signficantly greater variety than Cluster 2 ($p < .05$), as well as Clusters 3 and 4 ($p < .001$). This means that, over the seven segments, participants from Cluster 1 continually switched between a larger set of interfaces than participants from the other clusters, who restricted themselves to fewer interfaces.



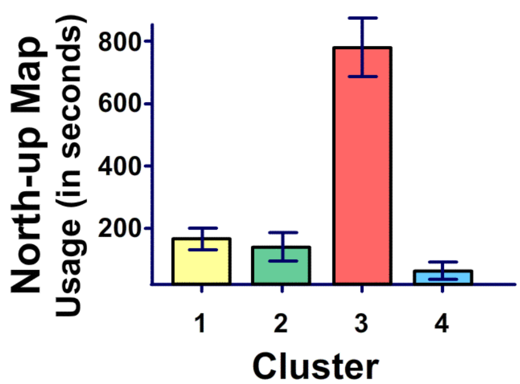
(a) Number of different interfaces invoked.



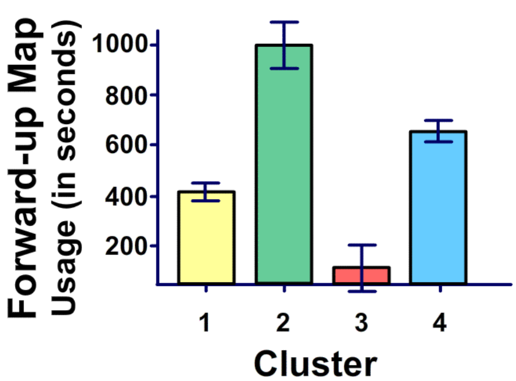
(b) Consecutive re-selection of an interface.



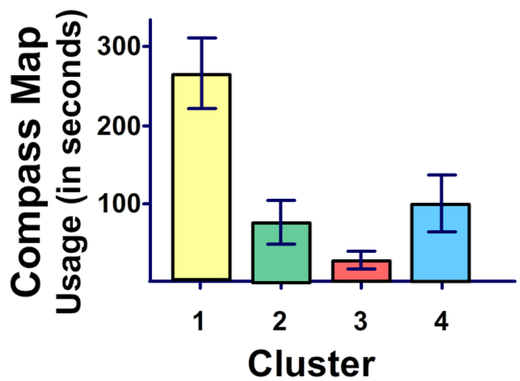
(c) Retained information without reference to the interface.



(d) North-up map interface usage time.



(e) Forward-up map interface usage time.



(f) Compass interface usage time.

Figure 5.12: Significant differences found between the four identified clusters.

Figure 5.12(b) shows the degree to which users were consistent in their interface selection, *Consistency* being defined as re-selection of the interface just used after the timeout mechanism removed the interface. In other words, despite the reminder that there are other possibilities for the user to select, users may choose to continue with the previous interface.

An omnibus ANOVA detected signficant differences in Consistency ($F(3, 26) = 5.67, p < .01$). A Bonferroni post hoc analysis indicated that the Consistency for Cluster 2 was significantly higher than the Consistency for both Clusters 1 and 4 ($p < .05$). Also, the Consistency for Cluster 3 was significantly higher than for Cluster 1 ($p < .05$). This means that users from Clusters 2 and 3 tended to re-select interfaces that they have been using but which were interrupted by the time-out mechanism while users from Clusters 1 and 4 were more likely to switch interfaces when asked to re-consider all the available interfaces.

Retention Ratio

We collapsed the active time, a, and passive time, p, over the interfaces and combined them into a ratio (p/a) to measure the effectiveness of the interface in helping a user navigate during the time immediately following the removal of the interface by the timeout mechanism. The larger this ratio, the longer the user was able to retain the navigation information and navigate without having to refer to the device for further information. We refer to this ratio as the *Retention Ratio*. An omnibus ANOVA detected significant differences in the Retention Ratios between Clusters ($F(3, 26) = 15.51, p < .001$). A Bonferroni post hoc analysis indicated that the Retention Ratio for both Clusters 3 and 4 are significantly higher than for both Clusters 1 and 2 ($p < .001$). Figure 5.12(c).

The low retention ratio of Clusters 1 and 2 indicate that a relatively large proportion of time was devoted to keeping a guidance interface actively displayed on the screen. In contrast, participants from Clusters 3 and 4 were not as reliant upon the devices for guidance and did not maintain interfaces on-screen as much.

Interface usage time

Overall interface usage time was recorded for all participants and an omnibus ANOVA was applied to each interface. No statistically significant differences were detected in usage time for AR ($F(3, 26) = 2.42, p = .089$) or the Radar interface between clusters ($F(3, 26) = .418, p = .74$). Significant differences were seen between clusters in total usage time for North-up maps ($F(3, 26) = 26.25, p < .001$), Forward-up maps ($F(3, 26) = 22.35, p < .001$), and the Compass interface ($F(3, 26) = 5.92, p < .01$). Post hoc Bonferroni analysis was applied to each interface with detected significance, which we report, below.

North-up map usage time in Cluster 3 was significantly higher than in all other clusters ($p < .001$), as can be seen in Figure 5.12(d). Users from this cluster spent 69% of their time using the North-up map (778 sec). The overall average percentage was 16% (185 sec) for the North-up map.

Forward-up map usage time varied widely and was significantly different between all the clusters ($p < .05$), as shown in Figure 5.12(e). Cluster 2 users relied upon the Forward-up map the most, using it for 72% of their interface usage time (915 sec), which was significantly more than users from all other clusters ($p < .05$). Cluster 4 users used the Forward-up map for 69% of their interface usage time (671 sec), which was significantly lower than users from Cluster 2 but still significantly higher than users from Cluster 1, where the Forward-up map was used for an average of 35% of the interface usage time (424 sec). Cluster 3 users had significantly lower usage of the Forward-up map than all other clusters at 10% (114 sec).

Cluster 1 users had the highest compass interface usage at 22% (262 sec), which is significantly more than usage by all the other clusters ($p < .05$), as can be seen in Figure 5.12(f).

5.5.2 Traversal Paths

Figure 5.13 visualizes the traversal paths taken by one representative participant from each of the four clusters. The paths are color-coded to represent the active interfaces (see caption for color-coding reference). Gaps within the paths represent the endpoints of each path where the participant was stopped and the mobile device was reset in order to prepare it for data collection on the subsequent path. The complete set of individual paths are found in Appendix C.

5.5.3 Characterizing cluster

With reference to the interface usage pattern, as depicted in the maps of Figure 5.13, and based on the significant differences detected, we make some observations of the characteristics of the clusters.

The high value for variety and low degree of consistency in Cluster 1 is evident in the colorful combination of interfaces invoked. Participants from Cluster 2 used the Forward-up map extensively and consistently. The low retention ratios of Clusters 1 and 2 are clearly exhibited in the traversal maps, which show very little gaps between interface usages. This indicates that almost continual guidance was requested which means that the user would have to reference the device frequently and, upon noticing the removal of the navigation interface, almost immediately re-activate an interface.

The gray sections on the paths of the representative participants from Clusters 3 and 4 show how the high retention ratios are manifested in long stretches of traversals without any active tools, represented by gray colored sections of the paths. While participants from both clusters preferred using map-based interfaces, participants Cluster 3 favored the North-up map whereas participants from Cluster 4 favored the Forward-up map.

The contrast in how the Forward-up map can be used in different ways can be clearly seen between Cluster 2 and Cluster 4. Participants from both these clusters preferred the Forward-up map but the participants from Cluster 2 seemed to prefer to have virtually continuous guidance while the participants from Cluster 4 was willing to traverse relatively long stretches without any navigational guidance.

5.5.4 User classification

Based upon the identified clusters and an interpretation of the various significant differences and other relevant factors, we attempt to classify users of each cluster by associating possible underlying meaning for the observed behaviors.

In order to do this, we make an assumption regarding the retention ratio: we assume it

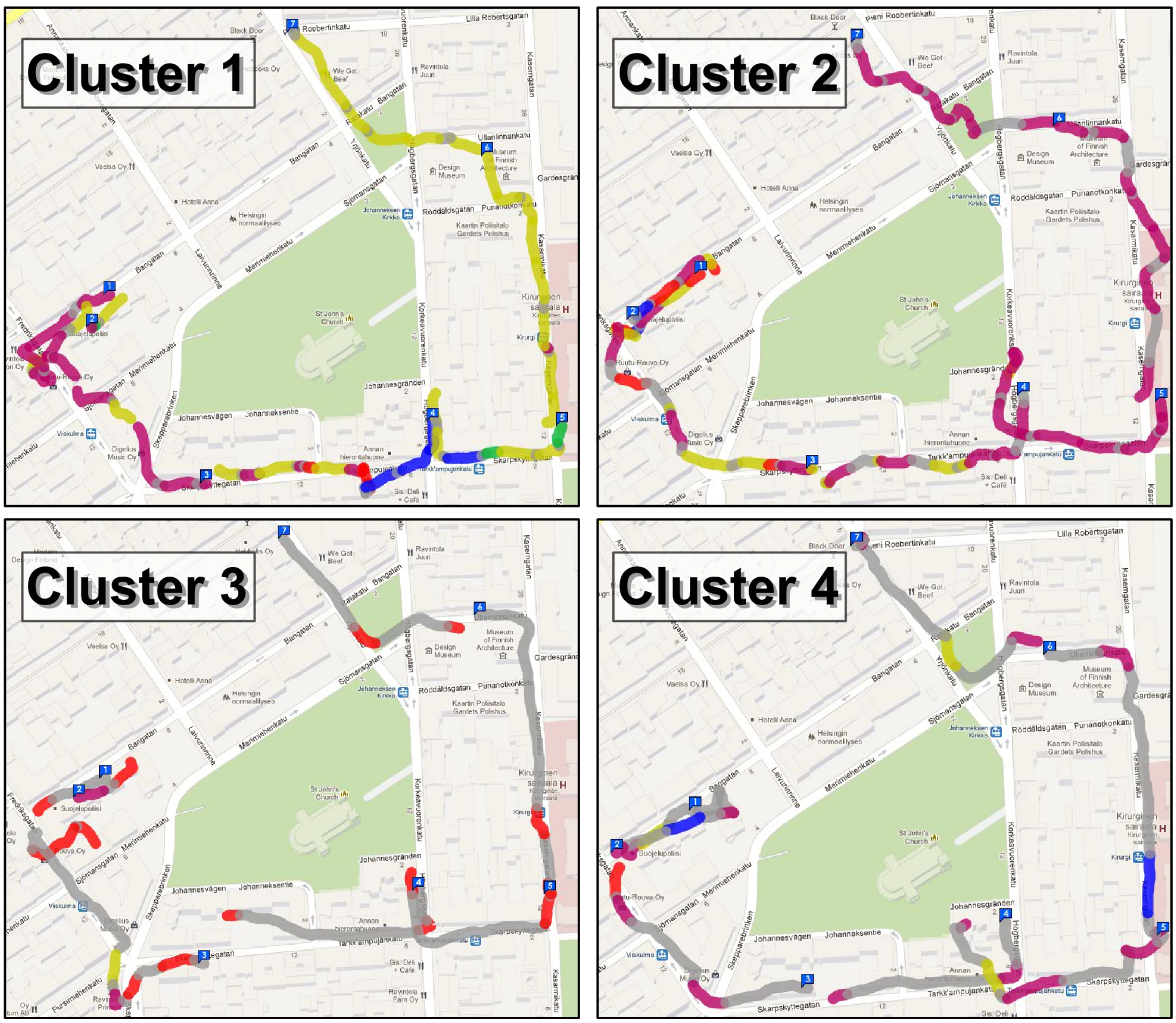
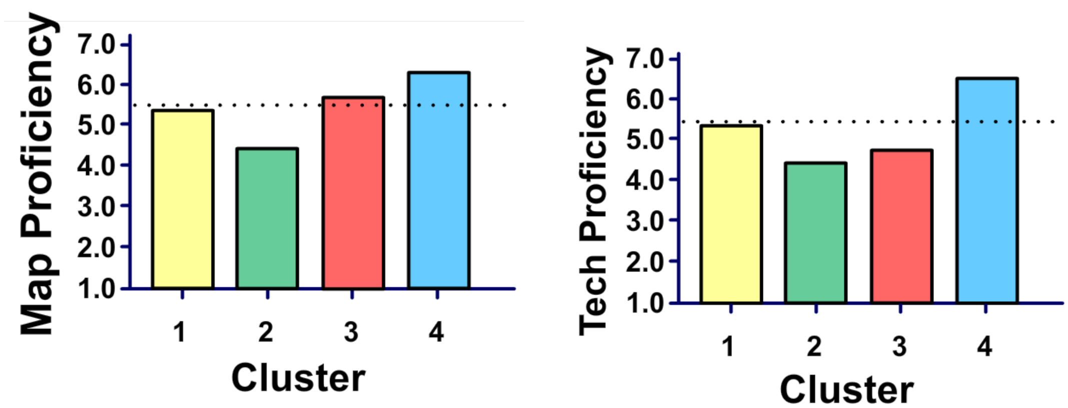


Figure 5.13: Traversal paths of representative participants from each of the four identified clusters. Interface usage is color-coded (red=North-up map, purple=Forward-up map, yellow=compass, green=AR, blue=radar, gray= no interface active).

is proportional to a person's ability or willingness to form mental maps. By definition, high values for the retention ratio correspond to users not actively employing a navigation aid, which suggests that they are able to memorize and retain the navigational instruction they had received. On the other hand, low retention ratio values correspond to users actively using the device, suggesting that the user has a need to have an active tool in lieu of referring to what they are mentally retaining.

Subjective measures

All participants were asked to assess their proficiency with maps and with technology on a 7-pt Likert scale with 1 being very weak and 7 being very strong. This is shown in Figures 5.14(a) and 5.14(b), where the overall perceived proficiency mean is shown as dotted lines (5.50 for map proficiency and 5.43 for technology proficiency).



(a) Self-reported map proficiency.

(b) Self-reported technology proficiency.

Figure 5.14: Self-reported profiency by cluster

Participants from Cluster 1 were fairly close to the overall mean values for both map and technology proficiency, (5.43 and 5.36 respectively). Participants from Cluster 2 had the lowest ratings (4.40 for both map and technology proficiency) while participants from Cluster 4 had the highest ratings for both (6.25 and 6.50 for map and technology proficiency, respectively). Participants from Cluster 3 had slightly higher than average perceived map proficiency (5.67) and lower than average perceived technology proficiency (4.67).

Cluster interpretation and classification

Participants from Cluster 1 appear to prefer immediate answers without having to process information. They perceived their map and technology abilities to be slightly better than neutral (which would be 4.0) but not very strong. They are observed to have jumped around interfaces pro-actively in order to find one that yields the simplest direction. We denote participants from this cluster as *Quick Answer Seekers* as they seem willing to interact with the navigation tool in order to find information that is useful for the immediate timeframe although potentially not far beyond it.

Cluster 2 participants had the lowest perception of their map and technology skills. Their usage behavior seems to indicate that they preferred to find an interface that delivers continuous information and rely upon it heavily. They may even do this to the point of overreliance, as P3 observed, "Because I look at this, I don't look around me." In a similar vein, P7 noted, "When navigating, you look too much at the screen." Based upon an apparent dependence on the guidance provided by the device coupled with a lack of active interface switching from the dominant interface, we designate participants of this cluster as *Passive Dependents* since participants from this cluster seem to prefer letting the navigation tool dictate instructions with a minimal of further tool-selection scrutiny once an acceptable interface is chosen.

Participants from Cluster 3 show a strong preference for North-up maps and, while they scored themselves relatively low on technology proficiency, they gave themselves higher ratings for map proficiency, which distinguishes Cluster 3 from the other clusters. Participants from this cluster may need to devote greater cognitive processing to interpret the North-up maps but may, as a consequence, build up better mental maps that decrease their dependence on having an active navigation aid. The North-up map is the digital navigation aid that most closely resembles the traditional paper map, which is the tool many think of when navigation through a city is needed. As P6 said, "In an urban environment, maps make most sense.” Of all the navigation tools in this experiment, the North-up map offered the least amount of technical novelty. We refer to participants from Cluster 3 as *Traditional Thinkers* since participants from this cluster seem to behave most closely to users of non-digital navigational aids.

Cluster 4 participants exhibited low consistency and jumped around the interfaces much like participants from Cluster 1, but their use of the Forward-up map was significantly higher than all other interfaces. Noting that Cluster 4 had the highest mean for the self-rated map and technology proficiency, we interpret the confidence of users in this cluster to be related to their apparent comfort with–if not enjoyment of–new technologies. The high retention ratio indicates that cognitive effort was applied. This translates into a willingness to explore interfaces and attempt to optimize extracted information to maximize effectiveness of the tool. P5 treated the comparison of interfaces almost as a competitive sport asking if it is acceptable “not using a tool if I’m confident.” We therefore denote participants from Cluster 4 as *Active Tinkerers* since they seem to possess a level of openess to activities that may be associated with intellectual effort and, possibly, also with intellectual satisfaction.

Figure 5.15 displays the identified behavioral types in relation to the interpreted factors that can help in navigation tool design.

On the high end of the scale for tool dependency as well as for the number of tools they are willing to use, Quick Answer Seekers may desire what they perceive to be the simplest information (e.g., directional pointer) available amongst the tools at their disposal. At the opposite end of both scales, Traditional Thinkers may not have a need for much navigation information beyond basic navigation support. Such users may be open to a minimal amount of non-essential support information (e.g., restaurant rating) but may not be as excited about new technologies as Active Tinkerers, who may appreciate them more in the proper context (e.g., AR when the destination is within view). Passive Dependents, meanwhile, may benefit from interfaces that attempt to wean them off excessive dependency (e.g., fading out the interface on straight paths to encourage greater attention to surroundings).

That the classification of the identified clusters into user behavioral groups may align with the results of previous studies conducted from substantially different methodologies is encouraging. Such a categorization helps us to solidify our understanding of how users

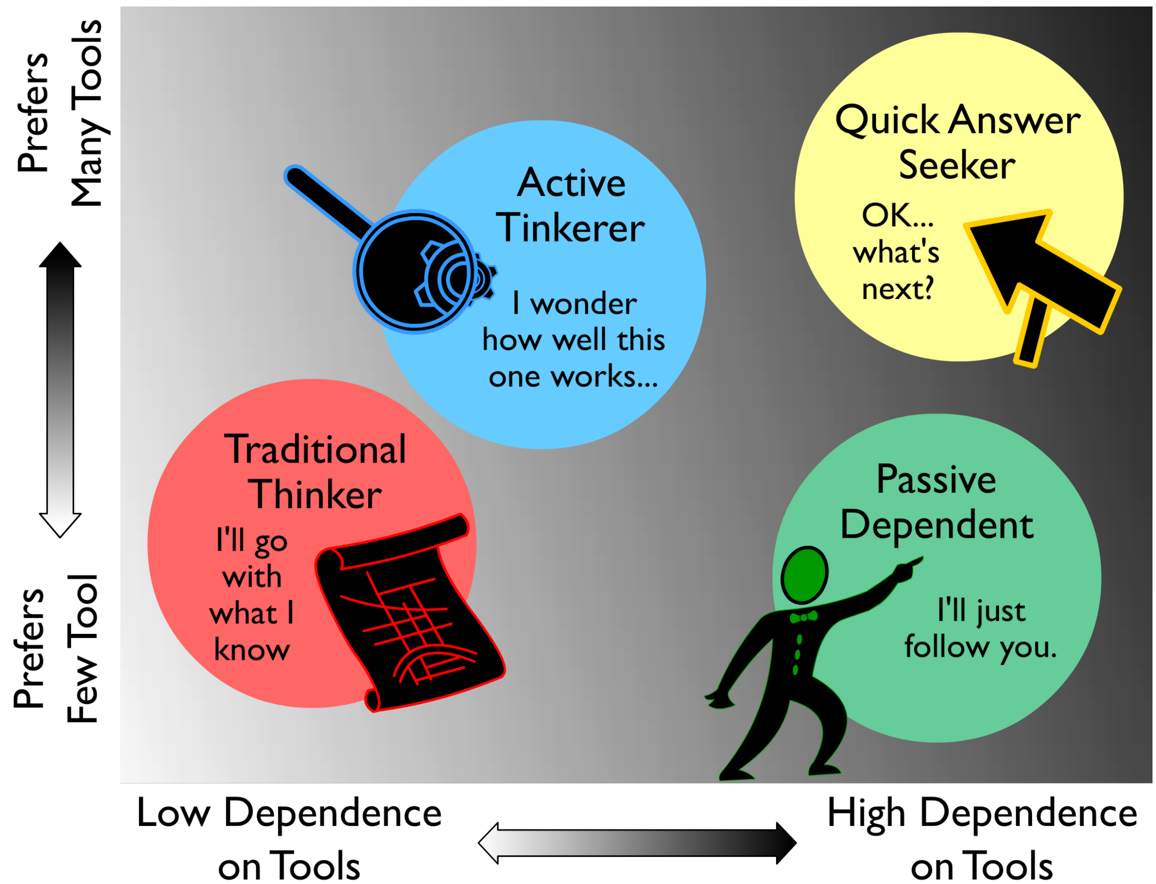


Figure 5.15: Classification of observed user behavioral types.

may behave with pedestrian navigation tools. We will examine this further in the following discussion section.

5.6 Discussion

The study sought to investigate the subjective factors related to how pedestrian navigation tools are chosen and used. In particular, this study was based upon the hypothesis that the various phases of a navigation task may lend themselves better to some tools over others and that this would be reflected through the selection and usage of tools. In this section, we discuss some implications of the subjective factors as well as phase dependency for AR interfaces. Beyond that, the wealth of data collected has yielded a rich set of insights into closely related areas also worth exploring further: the domination of Forward-up maps, the use of our user classification for interpreting usage behavior, and the alignment of our user classification with those of related studies. We will examine these areas in turn.

5.6.1 Perception of, performance with, and preferences for Pedestrian Navigation Tools

Although pedestrian navigation interfaces are often evaluated with user studies where users exclusively use the interface in question, it is not clear if results from interfaces tested independently would apply in a multi-interface environment. The findings of the present study suggest that user perception of navigation interfaces judged separately may be good indicators of actual usage preferences in an environment where the interfaces are offered collectively. However, it appears that there may be cases where usage preferences are more consistent with self-reported perception than with performance measures.

Although one typical standard for judging an interface is its time-on-task efficiency, from a user's perspective, performance measurements for such tools may not be the best indicator of how appealing a tool is. For example, despite the compass interface yielding the best average walking speed, its actual usage was relatively low. A possible reason for this is that the compass tool suffices for simple navigation tasks (e.g., straight-line traversal) allowing top speeds to be attained easily while non-trivial navigation tasks—such as avoiding obstacles (e.g., buildings)—may require more sophisticated tools that are, as a result, associated with slower speeds. Consequently, while the speed measurement is potentially robust and sensible in a mixed-interface environment, the short duration of usage may not properly capture the tool's true utility if no other tools were available. The Forward-up map interface, on the other hand, resulted in slightly slower walking speed but was heavily favored in actual usage.

This, of course, is potentially a reflection of the experimental design since offering interface choices within a navigational task is necessarily at the expense of measuring the efficiency of particular tools exclusively over uninterrupted sessions. Short bursts of speed may contribute disproportionately to the high performance of certain tools but tools offering occasions of efficiency may still not be chosen very often in a multi-interface environment.

Although the training phase supported exclusive tool usage, it was not part of the experiment proper and was not counter-balanced between the participants.

In a single tool environment, users are limited to using what is available and, in making do with what they have, may use a tool that is only effective for quick and small pieces of information. In that case, they may use a tool inefficiently in lieu of other options. However, when presented with alternative tools, users may make more efficient and effective use of the set of tools in combination. In such a setting, a tool that yields small units of information may only be utilized when it is considered effective and, in that case, the time-on-task measurement may differ greatly from a situation where the tool is tested in isolation. In a multi-tool environment, such experiences may help users to choose tools more strategically.

Our results seem to suggest that performance may not be the primary determining factor in the usage and adoption of a navigation tool. We were encouraged by the detection of a growing correlation in tool usage between consecutive navigation tasks which may be evidence of participants learning to settle with particular subsets of tools because they find those tools effective or otherwise appealing. Such behavior aligns with the claims that the adoption of a navigational aide is based more upon a causal sequence of navigational user experience rather than on performance and that the acceptance of navigation tools develops over time with increasing trust for a tool based, in part, on the clarity of information provided leading to trust in a system and the perception of lack of disorientation [2].

Applying this to the observed usage behavior, we can see that the mental rotations required in North-up maps may inhibit information clarity while the sensitivity of the compass and AR interfaces to GPS fluctuations may diminish both trust as well as clarity. Although the radar interface tried to offer a complete context by using a logarithmic scale to ensure that the destination is always within view (unlike the compass or AR interfaces), the distortion inherent in such a non-linear visualization may serve to confuse users, as well, since it was not intuitive. The Forward-up map provided clear and (assumed) trust-worthy information, which led to its acceptance as observed in the increased usage of Forward-up maps over the segments. Our observations seem to support studies that seek to measure user preference in terms of utility and user choice rather than efficiency [89]. In particular, in alignment with what we had set out to do, there may be some phase-dependencies that indicate users would spend more time with AR navigation tools as they near their destination.

5.6.2 Navigation phase and AR usage

The observed decrease in Forward-up map selection and the corresponding increase in AR selection between the middle and end sections of navigation may speak to phase-based behaviors we had hoped to observe to a greater degree. Although small when compared to the gap between the interfaces, the changes nonetheless seem to indicate a preference for non-survey contextual guidance after an initial overview with survey-based guidance. The jump of AR usefulness ranking from last to second in the last two phases shows an perception of its potential applicability for that stage of a navigation task. The relative increase in actual AR selection in the middle phase may point to users optimistically seeking out the destination visually before it is within range to be considered an end phase activity.

5.6.3 The preference for Forward-up maps

The overwhelming domination of the Forward-up map interface was not expected and risked overwhelming our attempt to undertake a balanced comparison between interfaces. That being the case, further scrutiny of the most widely used interface in our study is in order. Generally considered an exo-centric survey tool that is a map enhanced for automatically aligning orientation, Forward-up maps can also be effectively used as an ego-centric directional tool and the advantages of the Forward-up maps directional information over the North-up maps fixed orientation are well known [26][79]. However, if the easing of lateral rotations was the sole benefit, then the AR interface should have fared better since it not only addressed lateral rotations but also eliminated the task of making correspondences between cartographic representations with real world features.

One possible explanation is that the correspondence advantages of AR are offset by the disadvantages of GPS inaccuracies being magnified. While all the interfaces received the same geographic location data, the effects of the integrity of the data on the tool varied widely. Erratic GPS signal may not be visible in map interfaces where each pixel of the display may represent several meters. AR interfaces, in contrast, works directly with the surrounding environment on a real-world scale, potentially highlighting sub-meter inaccuracies over large subtended angles. Slight signal fluctuations that may be all but hidden in maps could be exaggerated when viewed through an AR interface, causing unstable rendering of virtual objects. The resulting visual jitter may diminish trust in the tools validity even though the original GPS signal is no less valid than what the maps receive. Adjusting and compensating for such signal noise require effort and may lead to user frustration.

Another possible factor is that Forward-up maps offer not only more information but also the illusion of more information. It is not clear if the surrounding map-like context of Forward-up maps is used as effectively as North-up maps since situation awareness has been observed to decline in users of Forward-up maps when compared to users of North-up maps [82]. This may speak to users focusing on the compass-like directional information of a Forward-up map more than the area survey information provided. Despite difficulties many people have using maps, the knowledge that maps have been–and continue to be–trusted and effective tools may make the Forward-up map attractive as a comfortably easy-to-use map-like tool, even if the cartographic context is largely ignored.

With all this said, it should be noted that some participants started with the Forward-up map but then switched to the North-up map and used little else. When asked by the experimenter why they chose to do that, one participant noted that the North-up map was "not as confusing" as the Forward-up map because it was fixed in place. One possible explanation could be that survey knowledge gained from map-based interfaces is diminished when such interfaces are used more as directional tools. The building of mental maps, it seems, may be better served by static maps that do not constantly rotate with the user. Seen another way, we may store mental maps better as static images than as mental movies.

5.6.4 Interpreting usage behavior from user classification

User behavior may not be so easy to decipher as simply interpreting tool usage alone: individual differences may play a large—if not primary—role in how proficient users are in wayfinding tasks and how they choose their navigation tools [95][69][78][50]. Our classification of users yielded some insights into how we can begin to codify otherwise complicated preferences. The identified categories allows us to target users by designing tool sets that can benefit them the most based upon the observed characteristics. With the identified categories, we can begin to grasp how different users may utilize the same tool differently. This, in turn, provides us with hints of how users may tax their cognitive resources, which are closely related to how they may form and use cognitive maps, a central component of our thesis.

The Forward-up map was the dominant interface for both the Passive Dependent and the Active Tinkerer groups. The former kept the device active for a majority of the time, while the latter was comfortable with the device being inactive almost all the time. This may be an indication that the Forward-up map fulfilled different roles for the two groups. Based upon the assumptions we have made, we claim that a Forward-up map fulfills dual roles, being both a survey tool as well as a directional tool. Survey and directional tools are very different by nature and, as such, may incur very different sorts of cognitive efforts from the user.

That Forward-up maps are survey tools is obvious: they are maps. Maps contain a tremendous amount of information that needs to be processed and the fairly large retention ratio for Forward-up maps in the Active Tinkerer group is therefore not surprising. It is presumably the considerable cognitive effort required to handle such survey tools that contributes to the information being retained for substantial periods of time.

The fairly small retention ratio for Forward-up maps in the Passive Dependent group, however, would not be expected if Forward-up maps supplied survey information that is used as cognitive maps. A possible explanation for this is that the Forward-up map is used more as a directional tool than a survey tool for members of this group. It may be possible that the map itself provides some support role but the primary information that allows the user to proceed with the navigation task may be the real-time directional information, which would require a greater frequency of references to the device in order to remain correct. By re-aligning with the direction the user is facing at all times, the Forward-up map is, in essence, acting like a compass.

One participant, who had ranked the North-up map as the preferred tool at the start of a navigation task but then swapped it with the Forward-up map to the second least favored tool in the middle and end phases, observed a desire "...to have an arrow that says where I am heading to in the North-up map."

Since the map context of the Forward-up map is functional as a navigation tool, survey information can be referenced even if it is not the primary information being delivered by the interface. In this way, a Forward-up map's dual role is neither fully a survey tool nor a directional tool at the same time but switching between the one and then the other for the user. Alternatively, for users who may have strong cognitive map abilities but are, by nature, anxious about their navigational progress, a map-based tool provides the quick verification needed to provide confirmation that would allay their anxieties.

5.6.5 Triangulating towards a classification of users

As noted, other attempts at classifying pedestrian navigation users based upon behavior have been undertaken recently. Given the physically exhaustive nature of conducting such studies, the number of participants is generally small. However, combining the results of smaller studies—particularly ones with different methodologies—can be an effective way of gaining insights into patterns that may otherwise not be so apparent. The potential agreement of the findings of the present study with other similar studies is encouraging. The degree to which the identified groups can be aligned despite the very different methodologies serve to substantiate and validate the classifications.

For example, the current study differs to Webber et al. [98] in approach and analysis but, with the exception of the Active Tinkerer group–which is unique to a multiple interface setting not studied by Webber et al.–there appears to be well aligned associations between the remaining groups. The Quick Answer Seekers align well with Webber's Constant Support and Information group since both groups seem to refer to their devices often and perform a minimum of information processing. The Passive Dependents can be associated with Webber's Least Effort and Inattentive group, whose members exert minimal effort but rely upon guidance. The remaining group, the Traditional Thinkers seem to be a good counterpart to Webber's Independent and Attentive group, both groups generally displaying the ability to either plan ahead or retain navigation information so as to reduce their dependency on their navigation tools.

The groups identified in our study also seem to align with the groups from Li's study [46]. The Quick Answer Seekers can be associated with Li's Heavy Map Users who made frequent references to their devices but seemed to gain little environmental knowledge, getting confused when they encountered dead-ends. Passive Dependents align well with Li's Text-based group, who continued with the route-based interface while the other participants turned to maps to handle more challenging wayfinding tasks. Finally, Traditional Thinkers seem to match Li's Low Frequency Map Users who seemed to develop good survey knowledge of the navigation area.

Our classification may have consequences for interface design: users who employ both modes of the forward-map tool may be fulfilling different but complementary needs that arise during navigation. Multiple means of interpreting presented information may allow for creative rendering of relevant information as interfaces become more dynamic and responsive to user behavior. For example, quick confirming glances may benefit from the highlighting of the immediate surroundings while longer glances may benefit from the presentation of more distant reference landmarks. We expect that, as tracking technologies improve, future research will want to re-visit how non-map navigation tools may compare with map-based tools. In particular, it would be worthwhile to gain insights into how the distinctions between Forward-up maps and non-map tools could be exploited to provide practical advantages beyond directional guidance. For example, could the potential for enhancing the surrounding environment with direct visual cues in AR offer greater situation awareness than what is offered in Forward-up maps? We explore this possibility further in Chapter 8.

5.7 Conclusion

With processing power growing and sensor technology improving at tremendous rates, mobile devices are able to support increasingly more sophisticated and varied interfaces for guiding pedestrians around urban environments. We set out to better understand how pedestrian navigators provided with a suite of tools—rather than just one tool—may select specific tools or set of tools to solve particular navigation problems by creating an application that forced users to periodically choose from a set of pedestrian navigation interfaces.

We observed learning effects occurring between navigation tasks indicating that users may have preferred strategies that they settle into as they become more proficient in navigation tasks with mobile aids. We also saw evidence of phase dependent preferences within navigation tasks indicating possible universal preferences for AR-based tools as they near their destinations. We further found results that supported the argument that performance may not dictate interface choice as much as perception of the effort a tool required. Based upon usage behavior recorded, we identified and described four distinct categories of users– Quick Answer Seekers, Passive Dependents, Traditional Thinkers, and Active Tinkerers– that align well with recent work and add to the corpus of data needed to classify users in order to optimize the presentation of navigation guidance information.

Like our previous study, as described in the last chapter, the data collected with respect to the AR interface was poorer than expected: the tool was hardly used. The present study offered a subjective reason for the observed low usage of the AR interface: it was perceived to require a great degree of effort to use. In the next chapter, we examine the potential underlying objective cause of this issue, which we hypothesize to be due to poor GPS data causing bad AR tracking, leading to a perception of AR being an untrustworthy tool. By addressing the issue of tracking directly, we may be better able to compare AR with other mobile pedestrian navigation tools.

6

Nav3: Simulating Perfect AR Tracking for Performance and Route Recall Measures

The last two chapters described studies conducted in the wild where poor GPS data may have adversely affected the AR interface more than the other interfaces. In this chapter, we investigate how the elimination of tracking errors associated with AR pedestrian navigation aids may impact our user studies. To do this, we created a virtual urban environment and conducted an experiment where participants navigated using simulated map and AR tools. By removing the tracking errors that can make AR difficult to use, we can focus our attention on defining an upper limit of how AR may affect navigational effectiveness and spatial knowledge acquisition in an ideal environment. The study described in this chapter, designated as Nav3, addresses research goals RG1 and RG2 (see Section 3.2) and tests hypotheses H1 and H2 (see Section 3.3).

6.1 Introduction

Given our interest in better understanding the potential role that AR can play in pedestrian navigation, our findings thus far have been unexpectedly inconclusive, save for the fact that users neither performed better with AR nor exhibited any extraordinary preference for

AR. We were unaware of any other empirical studies comparing maps and AR pedestrian navigation tools before we began our work but, unbeknownst to us, a group from the Ways2Navigate group at the Technische Universität Wien was conducting a similar study independently and at around the same time [74] also using target-based AR guidance cues. The fact that our two studies yielded consistent results led us to search for fundamental and systemic issues that may have affected how users perceive, use, and perform with AR-based pedestrian navigation tools. From observations, user feedback, and discussions, we suspected that outdoor tracking inaccuracies may be the primary factor in limiting user interest and performance.

Because the issue of poor outdoor tracking is a known problem and will not likely be solved in the immediate future [57], we took what we believed to be a sensible alternative in order to pursue our research goals: we created a testbed using virtual environment (VE) technology so that position information would be precisely defined at all times. This chapter describes our first experiment in this setting, which tested our hypothesis that AR would yield faster traversal time in guided navigation tasks but produce lower quality route knowledge. Assuming outdoor AR tracking technology will continue to improve, our results may define an asymptotic limit that real world tools can strive to approach.

6.2 Background

There is a long and extensive history of using VE to simulate real world navigations tasks and a large body of work has established the validity of using VE to gain insights into real world navigation, including [15][42][93][94][101]. Given the evidence that, for constrained movement within exploration of large virtual environments, users of desktop platform may out-perform more immersive systems [17], we chose to create a fairly restricted interface for navigating through a VE that would allow the participant to focus on the task of wayfinding rather than managing the interface to control movement.

In addition to navigation studies, VE has been used to test and evaluate GPS-enabled mobile devices such as inspecting potential annoyances of mobile device usage [33], which is aligned with our interest in investigating location-based mobile device usage. However, our research relates to the measurement of navigation efficiency and acquisition of spatial knowledge rather than perception of mobile device usage, so there is a need to integrate techniques for measuring acquired spatial knowledge into our VE system.

Traditional measures of spatial knowledge in the real world have been largely based on techniques that involve the recollection of absolute and relative distances traversed and directions to visited waypoints [22] as well as the creation of sketchmaps [6]. While sketchmaps have been shown to reflect spatial knowledge of virtual environments [4], our interest lies more with route rather than survey knowledge, which sketchmaps tend to capture. Route knowledge is generally based upon tests that demonstrate an ability to specify relative directions and route distance from points along a given path. However, while route distance estimates may be comparable between the real world and VE, disorientation may result far more readily after turns in VE than in the real world [75]. Since route knowledge is procedurally-based and is often stronger when direct traversal experience is involved [87][55], another approach may be available: participants can be asked to re-traverse the route to demonstrate the strength of their mental map [34]. Since speed and method of movement can be controlled and made to be less demanding without loss of complexity when compared with real world environments, we adopt this strategy in our system for the present study.

6.3 Study Design

We conducted a study to evaluate user performance, perceived effort, and route recall in traversing a path through a virtual environment with simulated AR navigation cues. Each participant was given navigation tasks that included a guided traversal followed by an unguided recall traversal of the same path. We employed a 2x3 between-subject design where each participant was assigned one of three navigation interfaces for guidance and asked to navigate two counter-balanced paths.

We were interested in how people performed with three different simulated navigation interface conditions:

- **Paper-like Map (MP):** A top down, exocentric 2D map view with fixed orientation (see Figure 6.1, *left*)
- **You-are-Here Map (MY):** A top down, exocentric 2D map view with fixed ori-

Figure 6.1: MP (left), MY (middle), and AR (right) interface conditions.

entation and a dynamic cue indicating the user position at all times (You-are-Here marker) (see Figure 6.1, *middle*)

- **AR:** Arrows rendered in the 3D environment showing the route to take (see Figure 6.1, *right*)

Both 2D maps are north-up maps with fixed alignment and indicate the paths of the route to follow in the navigation task. MP is meant to represent standard maps without satellite data, from the common paper-based map to digital maps provided by mobile devices without GPS support. MY, on the other hand, simulates digital maps that use GPS information to track the user in order to dynamically render the current device position.

The AR interface showed the route the participant was meant to follow rendered as a path with directional arrows projected directly onto the ground in the virtual environment, as shown in Figure 6.1 (right).

Both navigation interfaces are hidden unless explicitly requested by the user pressing on the $\boxed{\textbf{1}}$ key of the computer keyboard and holding it down. This interaction mode was chosen in order to discourage users from simply keeping the navigation interface visible at all times thereby making it difficult to judge the amount of navigation guidance needed. It also simulates interaction with a handheld device where the user stops to hold up the device in order to see AR cues. Additional information regarding the navigation interfaces are given in Section 6.3.4, which describes the software developed in greater detail.

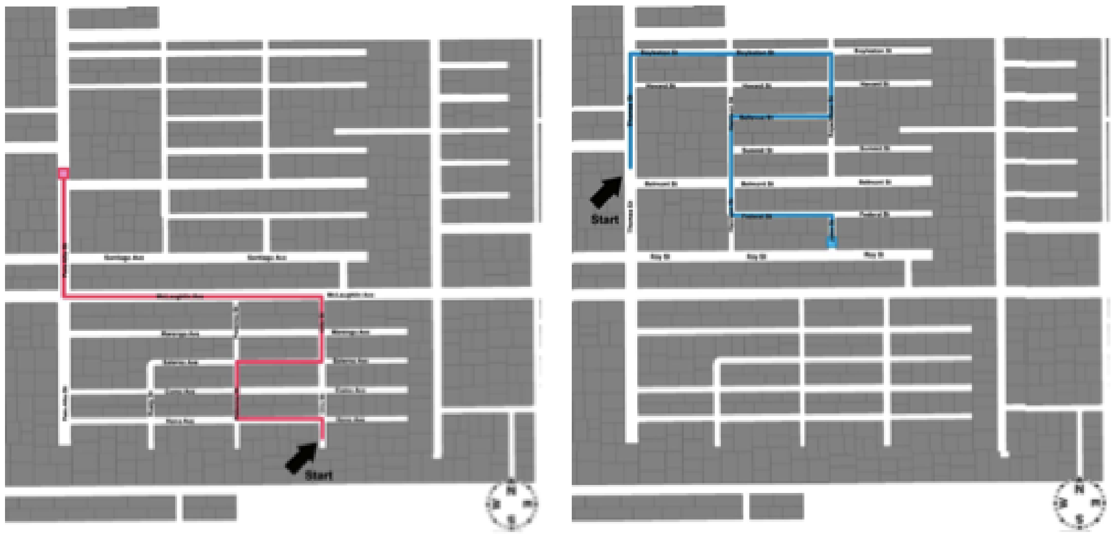


Figure 6.2: The two paths used in the desktop study, as shown in the map-based navigation tool.

6.3.1 Environment

The paths were created to represent a fictitious urban environment where streets were all aligned along one of two orthogonal axes. Buildings were textured with images of real or generated realistic faades. Two paths of approximately 850 meters and designated A and B, were created for the study. Path A included 11 decision points and 6 turns. Path B included 13 decision points and 6 turns. Path B was slightly longer than Path A but the two paths were otherwise comparable with respect to landmark saliency, navigation difficulty, etc. The paths are shown in Figure 6.2.

Large directional signs were placed at the start of the paths to indicate the initial orientation the participants needed to take, as shown in Figure 6.3. Once moving (how a participant moves is described in Section 6.3.4), the participants would use either their assigned navigation tool to follow the path or, in the unguided mode, recall as best as they could, the path to follow from memory. The timing of the traversal is triggered after the participant has moved past the end of the signs. Invisible barricades were set up so that participants that wandered off the paths would only be able to traverse for a small but non-trivial distance. This is to ensure that participants had indeed committed to following

Figure 6.3: Direction signs that are integrated into the virtual city provide initial guidance for participants starting the simulation.

a path which would be considered a navigation error. After traversing the equivalent of approximately 10 meters on the wrong path, the participant is stopped and instructed to return to the last decision point to correct the wrong turn. To guide the user back, a traffic cone is rendered in the center of the decision point where the wrong turn was made, as shown in Figure 6.4. Once they return to the decision point and proceed with the navigation task, the traffic cone is removed from the scene; if the user should turn around again from further away, there would not be a new visual cue to indicate where the last decision point was. In this way, we try to mimic the process typically taken in real world experiments where users are required to stay on a pre-defined path that are not distinguished in any way from other possible paths. In such scenarios (e.g., [60]), mistakes are corrected by the experimenter so no permanent visual cues are given beyond what previously existed.

To provide orientation, three of the four ordinal directions had visual landmarks placed far away enough so as to remain largely stationary, as shown in Figure 6.5. To indicate "north" (upwards on the vertical axis of the map), a model of the Tower of Babel is visible in the distance. "East" is associated with a mountain range while the Petronus towers

Figure 6.4: After committing to a wrong turn, a warning sign is shown and a traffic cone appears at the decision point (intersection) where the mistake was made.

indicate "west" in the VE. No landmarks exist for "south" which is unique due to the absence of any distant landmarks. Providing such fixed landmarks is similar to having the sun or some other visual cues that provide participants with a sense of orientation [14].

Street signs were placed at every intersection, an example of which is shown in Figure 6.6. The map tools labeled the corresponding cartographic representations of the streets while the AR tool did not reference the street names. No explicit waypoints were defined except for the final destination and it was only when participants had reached the final destination that a confirmation of the successfully completed journey was given.

6.3.2 Procedure

Participants were assigned workstations which were prepared with web browsers already displaying the consent form, which they had to read and agree to before proceeding. The browser then loaded a demographics survey followed by two questionnaires to assess the participants self-perceived comfort level with technology and maps (see Appendix D).

After completing the surveys, a 3D virtual environment was loaded for training. The

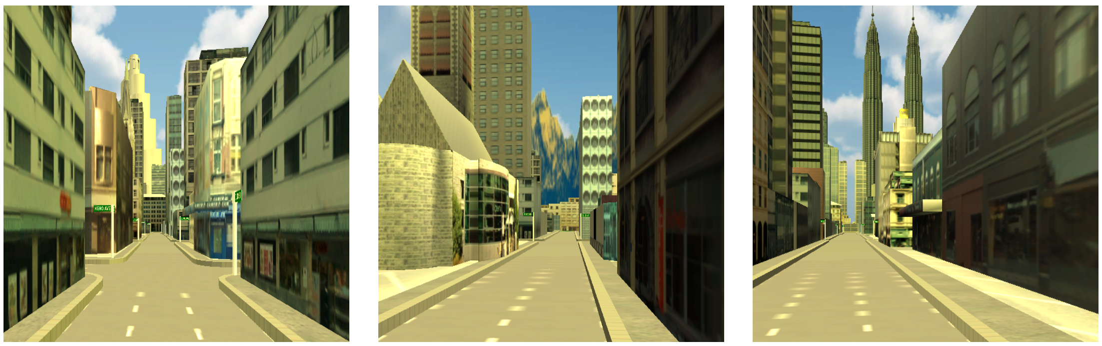


Figure 6.5: Landmarks indicating ordinal directions: Tower of Bable is North (left), Snowcapped mountains is East (middle), and the Petronus Towers is West (right); South is uniquely free of distant landmarks.

Figure 6.6: Street signs were placed on opposite corners of every intersection.

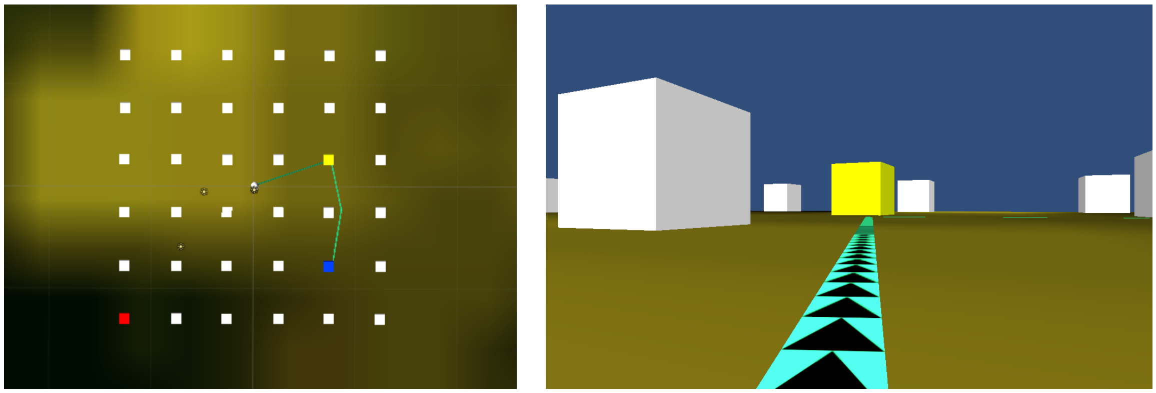


Figure 6.7: The interface training environment is an abstract world of cubes to familiarize the participant with how to use the mouse and keyboard to control movement in the VE.

participants were instructed to navigate a virtual environment defined by a collection of cubes laid out in a grid pattern. This was to help the participants become familiar with the controls that would be used in the actual experiment.

Depending on the condition assigned, the navigation tool was either a map showing the path they needed to follow (in the MP or MY conditions) or they would see a projected path showing them the way to the two stops in the cube maze (in the AR condition), as shown in Figure 6.7.

Upon completion of the training task, the participant was given the first of the four navigation tasks in the experiment. Between each navigation task, an interstitial screen was displayed with a description of the next task. This allowed the participant to take a brief break and to continue when ready. The trial proceeded as follows:

- **Task 1:** The participant was asked to navigate either Path A or Path B (counter-balanced between participants) through the virtual environment by following the guidance provided by the given navigation tool.

- **Task 2:** The participant was returned to the starting point of the path just completed and asked to navigate through the same virtual environment, following the same path previously traversed, but without the use of a navigation tool (which is disabled).

- **Task 3:** The participant was placed in another location in the virtual environment and asked to navigate through the alternate path (Path B or Path A), as depicted by the same assigned navigation tool.

- **Task 4:** The participant was returned to the starting point of the path just completed and asked to navigate through the same virtual environment, following the same path just traversed, but without the use of a navigation tool.

Between the third and fourth tasks (i.e., immediately after having used the navigation tool for guidance through the second path), the participants are given a System Usability Scale survey (SUS) [9] (see Appendix G) and a NASA Task Load Index Survey (TLX) [61] (see Appendix F). After the navigation trials, the participants were also given a post-test questionnaire including the opportunity to provide any thoughts and comments regarding their experience (see Appendix D).

6.3.3 Hardware

Our system was deployed on standard desktop computers based on Intel i7-2600 3.4 GHz processors which had 8 gigabtyes of RAM with standard keyboard and mouse input devices. Each computer was attached to a 21-inch flat-screen monitor with resolution of 1920x1080. Content was delivered over the internet so critical 3D components of the simulation were pre-fetched to avoid network latency issues effecting the user experience or performance.

6.3.4 Software

We created a testing environment that simulated completely accurate positioning in a virtual outdoor setting. Dubbed SPART, for *Simulated Perfect Augmented Reality Tracking*, it is a virtual city that supports the performance timing of navigation tasks using simulated AR-based tools in a virtual outdoor setting. We used the Unity3D[1], CityEngine[2], and custom-made 3D models to build the virtual environment. The application was deployed through a web interface and was used in full screen mode.

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[1] http://unity3d.com/

[2] http://www.esri.com/software/cityengine

Figure 6.8: Screenshot of the SPART environment with the map-based tool in view.

The 3D environment was experienced from an egocentric first person perspective. Movement was kept constant at a realistic pace of standard walking speed based upon the measurements used in the virtual environment. It was observed that this speed is considerably slower than the standard walking speed employed in typical first person shooter games. However, given the action-based nature of such games, unrealistic speeds is not only acceptable but desirable. In our case, we wish for participants to have the opportunity to observe the surrounding environment as they walk within it and so it was important that the movement speed be kept at a pace equivalent to an actual walking speed of approximately 5 km/hr.

Movement control was through the use of standard mouse and keyboard interfaces. The mouse controlled the turning of the head laterally, with the horizontal displacement of the mouse used to calculate the angle turned, while vertical tilting was disabled. Walking was activated by pressing and holding down the $\boxed{\textbf{W}}$ key and the user walked in the direction that the head was facing. Releasing the key would stop the walking process. To simplify the controls, no other key was enabled for movement control (i.e., the $\boxed{\mathsf{A}}$, $\boxed{\mathsf{S}}$, and $\boxed{\mathsf{D}}$ keys from the standard WASD game character control were disabled) and movement was restricted to forward motion (i.e., in a direction aligned with the viewpoint).

The navigation tool was invoked by pressing and holding down the $\boxed{\mathsf{1}}$ key. Walking was suspended when the navigation tool was shown. It was resumed, if the $\boxed{\mathsf{W}}$ key was depressed and the $\boxed{\mathsf{1}}$ key was released. Implementing the tool activation in this way allowed us to have a precise count of the number of times a participant used a navigation interface.

Map Interface

The map-based navigation interface was shown in the lower left hand corner of the display, as shown in Figure 6.8. Two types of maps were created: one with a You-are-Here marker (that indicated where the user was at any given time) and one without. As previously noted, both maps were north-up maps, which did not rotate to align with the direction the user was facing.

Street names were shown on the map and users were able to, using the $\boxed{<}$ and $\boxed{>}$ keys, zoom in for greater detail or zoom out for a larger overview of the area. Panning of the map was accomplished using the directional arrow cursor keys on the keyboard.

The route the user was meant to follow was shown as a colored path on the streets of the map. The destination was simply where the path ended.

AR Interface

The AR interface was shown as projected paths onto the virtual street that the user traversed, as previously shown in Figure 6.1. The path included arrows to indicate the direction to walk along, which may be useful in situations where users wandered off the path and needed to recall which direction along the path to follow when they returned to it.

The path was rendered as an object in the 3D environment, hovering a few inches off the virtual streets. It was properly occluded by the buildings in the environment and shown in a color that was clearly distinguishable from the actual surroundings. This is in contrast with our previous experiments, as described in Chapters 4 and 5, where the final target was shown so that its direction with respect to the user was clear but the actual path to follow in order to negotiate around obstacles, such as buildings, was not explicitly provided. By removing the extra work the user would have to do to strategize a route to the destination, it is assumed that the process of navigation would be made easier. However, this may not be taken for granted: a study undertaken after the completion of our outdoor study (see Chapter 4) by the Ways2Navigate project at Technische Universität Wien [32] found that path-based AR cues yielded significantly higher cognitive workload than maps.

Data Collected

All data in this experiment was collected through the web browser. The virtual environment data was sent over the network to a server that saved it to a database. After it was observed that some data transmissions were corrupted and therefore unusable for analysis, a redundant set of data was saved in the client application and sent at the end of the trials as an e-mail for manual handling to fill in any data lost in the real-time transmissions.

The following subjective data based upon self-reported information was collected:

- Basic demographics (age, gender, etc.)
- Technology proficiency survey (Appendix D)
- Sense of Direction survey (SBSoD) (Appendix E)
- System Usability Scale survey (SUS) (Appendix G)
- Task Load Index survey (TLX) (Appendix F)
- Feedback and comments

Objective data was logged by SPART for following measures:

- Total path navigation time
- Number of erroneous turns made
- Number of times the navigation interface was invoked
- Total time the navigation interface was used
- Total time spent walking

6.4 Results and Analysis

In this section, we present the results from the study. We report on the participant pool as well as the subjective and objective data collected. We also describe the analysis of the data.

6.4.1 Participants

A total of 90 participants (21 females) were recruited with age ranging from 18 to 26 (M=19.83, SD=3.39). 71 successfully completed the study. The MP and MY conditions had 25 participants each and the AR condition had 21 participants. All were students from the School of Art and Design at Victoria University in Wellington, New Zealand. The students were all either first-year architect students or post-graduate (masters degree) architect, design, or landscape architecture students.

6.4.2 Objective Data

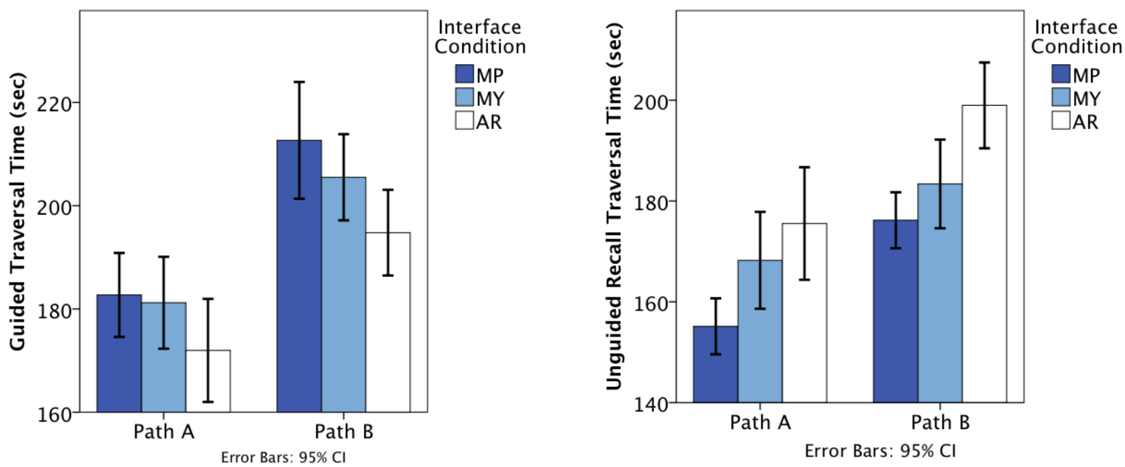
We collected objective data for time-on-task performance, navigation accuracy, and tool usage in terms of request frequency and total usage time.

Performance Results

Significant differences in time-on-task performance for Guided traversal as well as Unguided Recall traversals were detected between MP and AR users, which were aligned with our assumption and hypotheses H1 and H2 (see Section 3.3). For each path, we conducted a 2 (guidance: Guided vs. Unguided) by 3 (interface: MP vs. MY vs. AR) mixed ANOVA for travel time, measured in seconds.

For Path A, no significant travel time main effect for interface was detected ($F(2, 68) = .85, p = .43$), but a main effect was found for guidance ($F(1, 68) = 16.79, p < .001$). There was also significant guidance*interface interaction for travel time ($F(2, 68) = 8.68, p < .001$). Path B yielded similar results: no significant travel time main effect for interface was detected ($F(2, 68) = .177, p = .84$), but a main effect was found for guidance ($F(1, 68) = 34.46, p < .001$). There was also significant guidance*interface interaction for travel time ($F(2, 68) = 14.26, p < .001$).

We conducted one-way ANOVAs for the Guided traversals on both paths and used Bonferroni post-hoc analysis to detect the pair-wise significant differences. As can be seen in the graphs of Figure 6.9(a), MP users took longest to complete the guided traversal (Path A: $M = 182.72s, SD = 19.70s$; Path B: $M = 212.65s, SD = 27.41s$). MY users were slighter faster (Path A: $M = 181.20s, SD = 21.57s$; Path B: $M = 205.50s, SD = 20.21s$). AR users took the least time to complete both of the guided traversal paths (Path A: $M = 171.97s, SD = 21.95$; Path B: $M = 194.77s, SD = 18.22s$). A significant difference was detected between MP and AR for the guided traversal of Path B ($F(2, 68) = 3.61, p < .05$) but not for Path A ($F(2, 68) = 1.70, p = .19$).

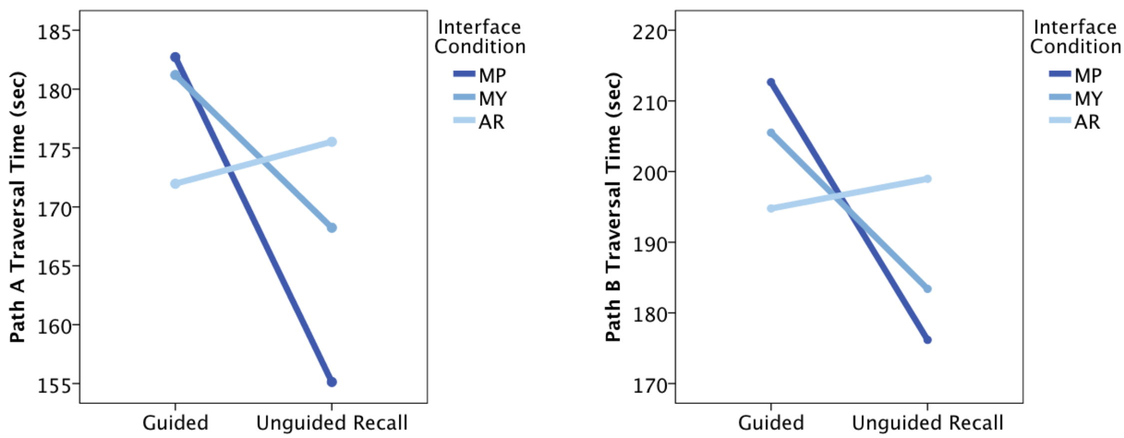


(a) Guided traversal time (b) Unguided Recall traversal time

Figure 6.9: Time-on-task performance for Guided and Unguided Recall traversals. (Error bars: 95% CI)

The results for the one-way ANOVA for Unguided Recall traversal performance was reversed from the guided performance for both paths, as can be seen in the graphs of Figure 6.9(b). MP users took the least time to traverse the paths entirely from memory and without any navigation aid (Path A: $M = 155.14s, SD = 13.46s$; Path B: $M = 176.18s, SD = 13.45s$). MY users took a slightly longer time to complete the same exercise (Path A: $M = 168.23s, SD = 23.29s$; Path B: $M = 183.39s, SD = 21.32s$). AR users required the longest time to complete the recall traversals (Path A: $M = 175.53s, SD = 24.53s$; Path B: $M = 198.98s, SD = 18.70s$). For Path A, participants who used MP were borderline significantly faster at recalling the path than MY users ($F(2,68) = 5.76, p = .050$) and significantly faster than AR users ($F(2,68) = 5.76, p < .01$). For Path B, participants who used MP were significantly faster at recalling the path than MY users ($F(2,68) = 9.32, p < .05$) as well as AR users ($F(2,68) = 9.32, p < .001$).

Figure 6.10 show how the travel times between the Guided and Unguided traversals differed between the interfaces. It can be seen that MP took the most time while AR took the least time on the Guided traversal and that this relationship was reversed in the Unguided traversal. Also, as is clearly depicted in the graphs, the Unguided traversal times took less time than the Guided traversal times for the map interfaces but, for the AR interface, the reverse was true: the Unguided traversal time took longer than the Guided traversal time.



(a) Path A traversal time (b) Path B traversal time

Figure 6.10: Guided vs. Unguided travel times for the interface conditions.

Navigation Tool Usage

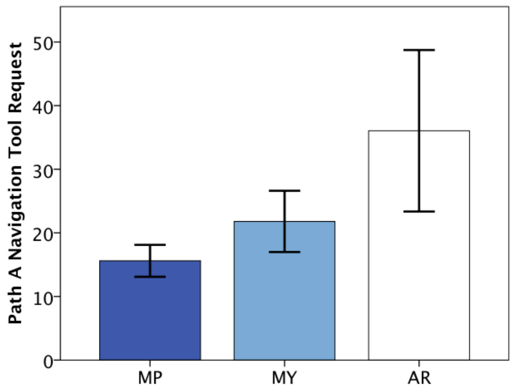
The number of times a participant requested guidance from the navigation tool was logged, as was the total usage time of the tool. Since the participant was required to keep the $\boxed{\mathbf{1}}$ key depressed on the keyboard to study the navigation information, the amount of time the key was depressed was an accurate indication of the amount of time needed to reference the tool. We found that people requested the AR tool more than the map tools on average, but the time spent per actuation of the navigation tool was signficantly less for AR than for maps.

Figures 6.11(a) and 6.11(b) show the average number of requests made for a navigation tool in each of the navigation conditions. It can been seen that MP was invoked the least on average (Path A: $M = 15.60, SD = 6.076$; Path B: $M = 19.44, SD = 8.29$). MY was invoked more often (Path A: $M = 21.80, SD = 11.67$; Path B: $M = 27.00, SD = 26.91$). AR was invoked the most on both paths (Path A: $M = 36.05, SD = 27.88$; Path B: $M = 35.57, SD = 23.52$).

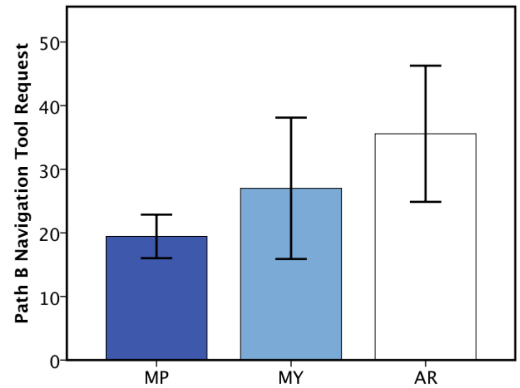
The total time spent using the navigation tools had the reverse trend, as shown in Figures 6.11(c) and 6.11(d). MP, though invoked the least often, required the most time from the user (Path A: $M = 25.68s, SD = 12.22s$; Path B: $M = 35.72s, SD = 16.48s$). MY required less time for both paths (Path A: $M = 20.96s, SD = 9.32s$; Path B: $M = 27.84s, SD = 12.27s$). AR took the least time (Path A: $M = 9.52s, SD = 3.95s$; Path B: $M = 11.14s, SD = 6.26s$).

The average time per use for a navigation interface is shown in Figure 6.11(e) and 6.11(f). It can be seen that AR (Path A: $M = .32s, SD = .11s$; Path B: $M = .34s, SD = .11s$) average time per use was lower than both MP (Path A: $M = 1.70s, SD = .62s$; Path B: $M = 1.93s, SD = .82s$) and MY (Path A: $M = 1.56s, SD = 2.33s$; Path B: $M = 1.97s, SD = 3.50s$).

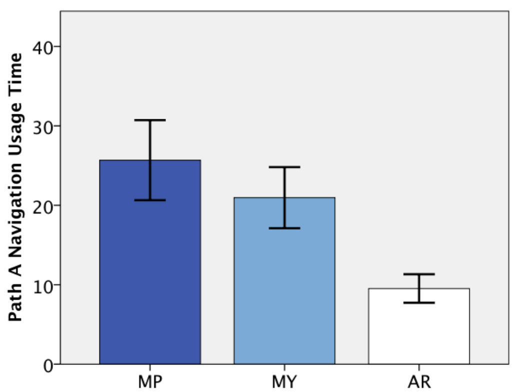
One-way ANOVAs were conducted for the recorded tool request count and usage time. For Path A, AR was requested significantly more than both MP ($p < .001$) and MY ($p < .05$). For Path B, AR was requested significantly more than MP ($p < .05$). With respect to time spent, significant differences were detected between AR and both MP and MY for both paths to $p < .001$ level.



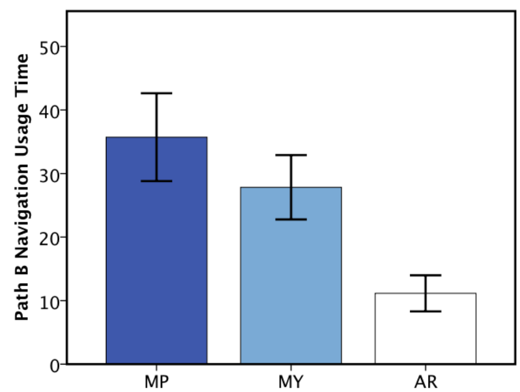
(a) Request count for Path A



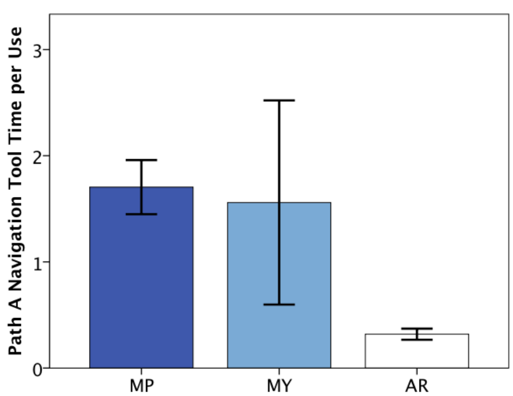
(b) Request count for Path B



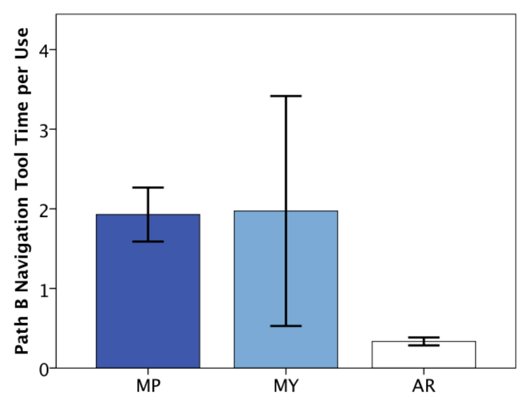
(c) Total usage time for Path A



(d) Total usage time for Path B



(e) Average time per use for Path A



(f) Average time per use for Path B

Figure 6.11: Navigation tool usage.

Accuracy Results

Accuracy was measured by the number of incorrect turns made by participants. Although participants who were being guided would ideally make no navigation errors, the nature of the guidance tool may be confusing or the participant may have been momentarily distracted resulting in a wrong turn being made. Therefore, in practice, errors were made by users during Guided traversals although they were substantially fewer in number than errors made during Unguided Recall traversals. Few errors were committed in the Guided traversals for all interfaces; significantly more errors were made during the Unguided Recall traversals. MP users also made significantly fewer errors than AR users in the Unguided Recall traversals.

We conducted a 2 (guidance: Guided vs. Unguided) by 3 (interface: MP vs. MY vs. AR) mixed ANOVA for accuracy for each path. For Path A, signifcant accuracy main effects were detected for both guidance ($F(1, 68) = 61.20, p < .001$), and interface ($F(2, 68) = 4.16, p < .05$). There was also significant guidance*interface interaction for accuracy ($F(2, 68) = 5.54, p < .01$). Path B yielded similar results: signifcant accuracy main effects were detected for both guidance ($F(1, 68) = 70.82, p < .001$) and interface ($F(2, 68) = 4.37, p < .05$). Again, there was significant guidance*interface interaction for accuracy ($F(2, 68) = 5.57, p < .01$).

For the guidance main effect, we followed up the omnibus ANOVA with a t-test using Bonferroni post-hoc analysis to identify pair-wise significance. Tables 6.1 through 6.3 list the results from guidance main effect calculations for errors for the MP, MY, and AR interfaces, respectively.

For the interface main effect, we followed up the omnibus ANOVA with a one-way ANOVA between interfaces for Guided and Unguided traversals. No significant differences were found between the interfaces for the Guided traversal of Path A ($p = .87$). For the Unguided traversal of Path A, a post-hoc Bonferroni analysis indicated that errors made by MP users ($M = 1.08, SD = 1.29$) were fewer than errors made by AR users ($M = 2.81, SD = 2.36$) by a significant amount ($F(2, 68) = 5.44, p < .05$).

The analysis for Path B was similar: No significant differences were found between the

MP Path	Mean	SD	p
A Guided	.28	.61	< .01
A Unguided	1.08	1.29	
B Guided	.20	.41	< .001
B Unguided	1.52	1.33	

Table 6.1: Errors comparison between Guided and Unguided for MP interface

MY Path	Mean	SD	p
A Guided	.20	.65	< .001
A Unguided	1.96	1.62	
B Guided	.52	1.046	< .01
B Unguided	2.00	2.27	

Table 6.2: Errors comparison between Guided and Unguided for MY interface

AR Path	Mean	SD	p
A Guided	.19	.68	< .001
A Unguided	2.81	2.36	
B Guided	.24	1.044	< .001
B Unguided	3.33	2.033	

Table 6.3: Errors comparison between Guided and Unguided for AR interface

interfaces for the Guided traversal ($p = .23$) but, for the Unguided traversal, a Bonferroni analysis detected that errors made by MP users ($M = 1.52, SD = 1.33$) were fewer than errors made by AR users ($M = 3.33, SD = 2.03$) by a significant amount ($F(2, 68) = 5.39, p < .01$).

6.4.3 Subjective Data

We collected subjective data for self-assessed map and technology proficiency, sense-of-direction abilities as well as perception of the interfaces based upon usability and workload questionnaires.

Self-assessed Map and Technology Proficiency Data

Participants were asked to assess their overall comfort with maps ("I feel comfortable using maps.") on a 7-point Likert scale (1 = Comfortable, 7 = Not Comfortable). They were also asked to complete the Santa Barbara Sense of Direction (SBSoD) survey (see Appendix E), which is a 15 question questionnaire designed to assess the test takers sense of direction based upon their answers to everyday questions regarding maps, navigation, and spatial awareness [25]. Most participants reported feeling comfortable with maps ($M = 5.49, SD = 1.27$). The SBSoD scores were somewhat lower, with smaller observed standard deviation ($M = 4.58, SD = .84$).

Participants were also asked to rate their comfort navigating within a virtual environment ("I feel comfortable navigating a 3D environment on a computer") on a 7-point scale. They were subsequently given a questionnaire that gauged their comfort and familiarity with technology (see Appendix D). Most participants reported feeling comfortable with technology ($M = 5.17, SD = 1.49$). The four question technology survey had a slightly higher mean score with lower variation ($M = 5.68, SD = 1.19$).

We calculated the Pearson r correlation coefficient between the pre-test self-assessment questions to see if the answers correlated. For the 7-point scale questions regarding map and technology comfort, there was a medium correlation ($r = .48, p < .001$). The scales on the map and technology comfort questions were reversed from the SBSoD and technology

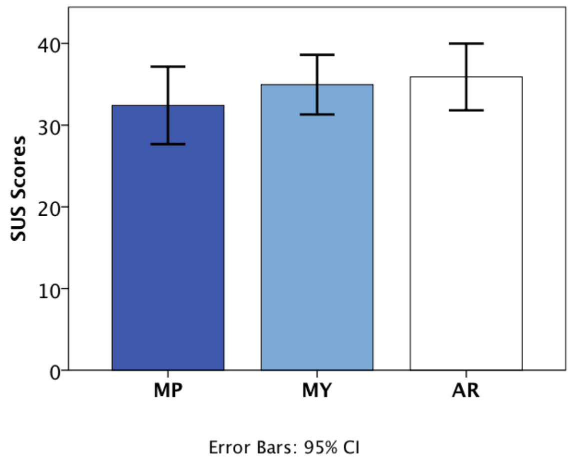


Figure 6.12: Results from the Standard Usability Scale survey.

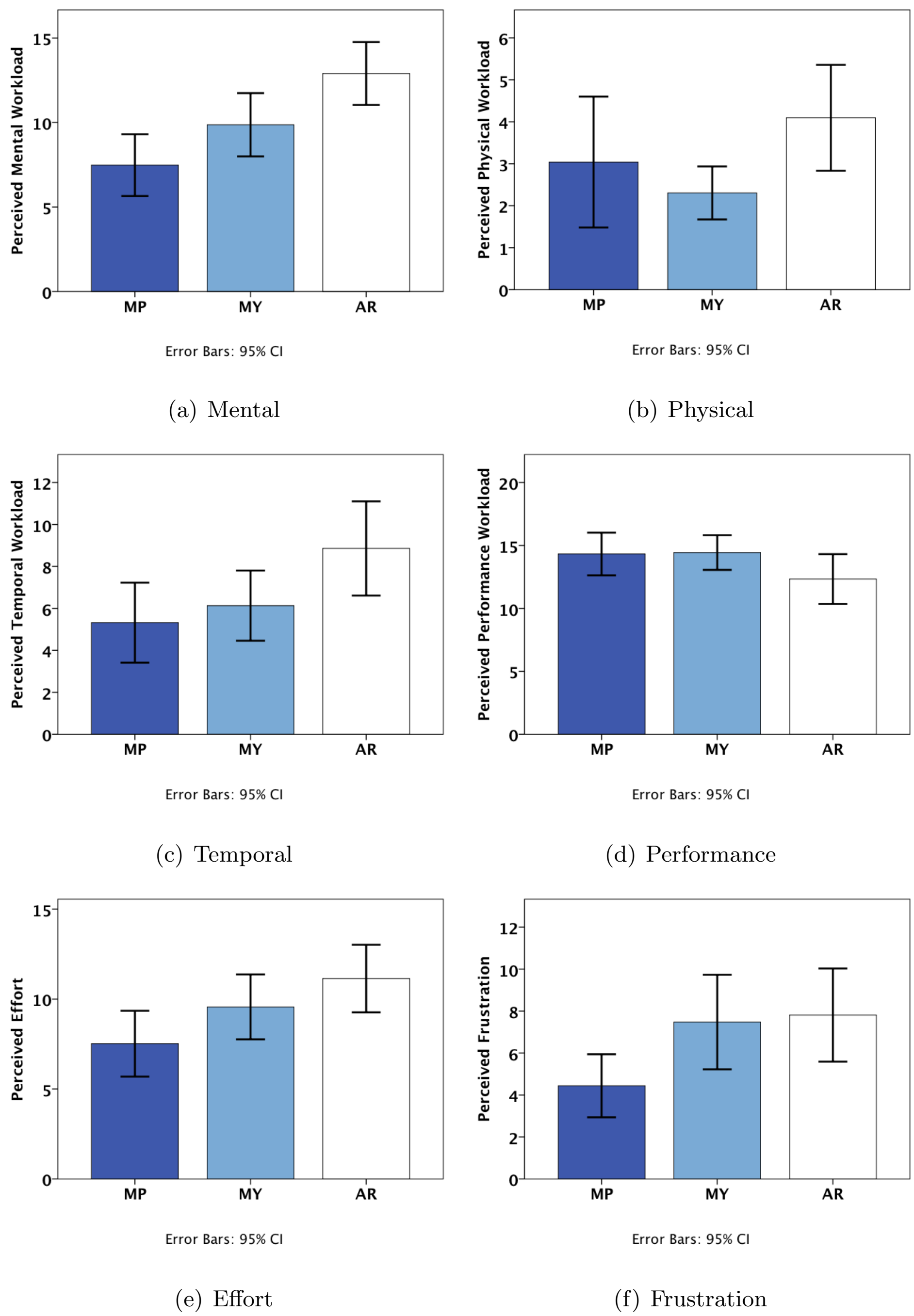
survey scales so negative correlations were expected and were indeed detected both between the map comfort question and the SBSoD score ($r = -.29, p = .015$) and between the technology comfort question and the technology survey ($r = -.47, p < .001$).

6.4.4 Perceived Usability and Workload

There was no significant difference in perceived usability between interface conditions. However, there was a significant difference in perceived workload between the interfaces. Figure 6.12 shows the mean SUS scores by interface. A one-way ANOVA applied to the scores for MP ($M = 32.42, SD = 9.74$), MY ($M = 33.42, SD = 10.54$), and AR ($M = 36.81, SD = 9.54$) yielded no significant differences between the interfaces ($F(2, 63) = .796, p = .456$).

The perceived effort for the interfaces, based on the NASA TLX (see Appendix F) are shown in Figure 6.13(a). An omnibus ANOVA detected a significant difference existed ($F(2, 66) = 9.11, p < .001$). A post-hoc Bonferroni analysis indicated the traversals using AR incurred significantly greater perceived mental effort ($M = 12.90, SD = 4.085$) than traversals using MP ($M = 7.48, SD = 4.43$), to the level of $p < .001$. MY ($M = 9.87, SD = 4.33$) was statistically equivalent to MP and just shy of incurring significantly less mental effort than AR ($p = .067$).

With respect to perceived physical effort, no significant differences were detected, as



(a) Mental (b) Physical

(c) Temporal (d) Performance

(e) Effort (f) Frustration

Figure 6.13: Results from the NASA TLX perceived workload survey.

shown in Figure 6.13(b), ($F(2.66) = 2.15, p = .124$).

Significant differences were found with respect to the perceived temporal effort between interfaces ($p < .05$). AR was perceived as requiring the most time ($M = 8.86, SD = 4.93$), which was significantly more than MP ($M = 5.32, SD = 4.62$). There were no significant differences for MY ($M = 6.13, SD = 3.87$) between MP ($p = 1.00$) or AR ($p = .144$). This is shown in Figure 6.13(c).

No significant differences between interfaces were found for perceived performance effort ($F(2, 66) = 1.99, p = .144$), as shown in Figure 6.13(d).

Perceived effort expended yielded a significant difference, ($F(2, 66) = 4.20, p < .05$) between AR ($M = 11.14, SD = 4.13$) and MP ($M = 7.52, SD = 4.44$). MY ($M = 9.57, SD = 4.18$) yielded no significant differences with MP ($p = .30$) and AR ($p = .67$). This is shown in Figure 6.13(e).

The perceived frustration levels are shown in Figure 6.13(f). Once again, a significant difference was detected between AR ($M = 7.81, SD = 4.88$) and MP ($M = 4.44, SD = 3.64$), ($F(2.66) = 3.89, p < .05$). MY ($M = 7.48, SD = 1.97$) yielded no significant differences with MP ($p = .076$) and AR ($p = 1.00$) for perceived frustration.

The combined TLX perceived workload and is shown, separated by interface, in Figure 6.14. A significant difference was observed between MP ($M = 7.02, SD = 2.63$) and AR ($M = 9.52, SD = 2.40$), ($F(2, 66) = 6.46, p < .01$). MY ($M = 8.30, SD = 1.97$) yielded no significant differences with MP ($p = .20$) and AR ($p = .27$).

We calculated the Pearson r correlation coefficients between the pre-test self-assessment questions and the post-test usability and workload surveys. A medium correlation was detected between the map comfort question and the SUS results ($r = .31, p < .05$) but, when analyzed by condition, was only evidenced for AR users ($r = -.47, p < .05$). The SBSoD scores exhibited small negative correlations with both the SUS scores ($r = -.24, p < .05$) and the combined TLX scores ($r = -.26, p < .05$).

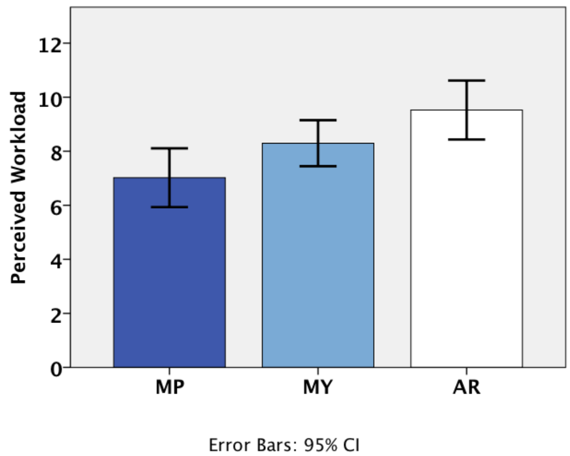


Figure 6.14: Results from the combined TLX scores.

Subjective and Objective Correlations

We calculated the Pearson r correlation coefficients between the subjective data (map comfort, technology comfort, SBSoD, technology survey, SUS, and combined TLX) and the objective data (time Guided, time Unguided, error Guided, error Unguided, navigation tool request, navigation tool usage time). Table 6.4 summarizes the results, including significant correlations detected. As can be seen, some significant correlations were detected between self-assessed proficiency (both map and technology) and in objective measures of Guided traversal and navigation tool request. A strong negative correlation between the sense-of-direction questionnaire and Unguided Recall errors made was also seen, as would be expected. We will examine these correlations further in the following section.

6.4.5 User Comments

At the end of the user study, users were asked several questions to help understand more how they remembered the path they were navigating and to give feedback about the interface. Users were able to write whatever answers they wanted in response to the questions. The questions were:

1. Did anything help you to remember the path?

		$time_G$	$time_U$	$error_G$	$error_U$	nav_{count}	nav_{time}
Map comfort	r	**-.23**	.11	-.23	.21	**.26**	-.13
	p	**.049**	.38	.059	.078	**.028**	.28
Tech comfort	r	.078	-.001	-.14	.032	.19	.077
	p	.52	1.0	.24	.79	.12	.53
SBSoD	r	.012	-.22	.035	**-.30**	-.13	.017
	p	.92	.061	.77	**.011**	.29	.89
Tech survey	r	**-.26**	-.14	.015	-.046	**-.29**	-.12
	p	**.031**	.23	.90	.70	**.014**	.31

Table 6.4: Pearson r correlation coefficient betweeen subjective and objective data. (Inverse box indicates 2-tailed significance, $p < .05$.)

2. What was frustrating about the computer interface?
3. Did the simulation capture reality?

We collected usable responses from 84 of the subjects. In terms of remembering the path navigation, using street signs was the most popular technique with 62 out of 83 people mentioning that they used street signs or street names. Buildings and landmarks were also very popular with 39 people mentioning the use of buildings or landmarks. Some subjects also used both buildings and street signs together. For example, one subject said "Mainly I used street signs but I also used the church and the double spired buildings." The least popular method was to remember the sequence of turns made or counting the number of roads passed, with only 22 people mentioning this. For example, "I remembered the way I had to turn and what number street to take off eg second street down or third." Apart from street signs, using landmarks, and remembering turns or counting streets there were no other navigation techniques use. This shows the importance of users having the cognitive ability to remember either streets, landmarks or turn sequences.

In response to the question about what was frustrating about the computer interface, 81 people provided answers. The most common response was the slow movement with speed issues being mentioned by 34 people. A typical complaint was "Slow walking, could be a lot faster, whilst still registering direction." Other common complaints were the mouse and keyboard input methods used (5 people) and the lack of variety in the buildings shown (7 people). For instance, one user referring to the standard game keyboard control keys, said "I would have preferred W,A,S,D navigation and use the mouse for controlling the camera." Another observed that "the buildings were similar in appearance and monotonous. The road signs couldn't been seen from very far away." However, 9 users felt that there was nothing wrong with the interface.

Finally, 78 subjects answered the question about whether the system captured reality. In general they were very positive with 50 of the users saying that the system captured reality from "averagely" through to "very closely." Only 12 people had negative comments. Many users felt that the system was close enough to simulate the methods that they used for navigation in the real world. For example, one user said "Quite closely. The use of street signs and landmarks was similar to navigation in reality." Another said "I think it closely resembles my abilities in a real world situation. I would use the same thought process. It closely captured my actual navigation and recall experience." However, some subjects thought that the visuals could be improved, and that there could be additional cues added that are present in the real world. One person said, "The buildings weren't very realistic so were hard to base the memory of the route by." And another said "Fairly closely but it could lack elements like people, sounds or smells which give bearings." In general though, the positive feedback indicated that even a simple simulation like this can be seen as realistic enough by users to test their navigation abilities.

6.5 Discussion

This study set out to investigate the potential performance differences between map-based navigation tools and AR in a simulated outdoor navigation environment that provided perfect AR tracking. The switch from a real world setting to a virtual world setting will undoubtedly have an impact on the user experience and on user behavior in ways beyond the obvious changes in surroundings. Nonetheless valuable insights could be gained with respect to the more fundamental relationship between the effect of a guidance tool on navigation and cognitive map formation.

Map vs AR: time & errors

Our results did indeed indicate that, in a virtual environment where AR tracking inaccuracies were not an issue, users exhibited better performance with the AR tool. This suggests that, as real world tracking technology improves, AR navigation tools will become more effective and therefore, more appealing, navigation tools. In addition to the main change from a real world to a virtual world environment, the nature of the AR tool was also changed: the route to follow was rendered in a "follow me" path rather than just the "target direction" indicator showing only the direction of the final destination. Because the "follow me" path tools require practically no decision-making responsibility for the user, it potentially offers a more efficient guidance tool than the "target direction" interface, which still requires the user to negotiate around obstacles, such as buildings.

The results indicate that participants were faster in the recall tasks after having used the map tools but were slower after using the AR tool. This is consistent with our hypothesis. In fact, the traversal time for the recall task using the AR tool took longer than the original guided traversal. This contrasts with the map users, where the guided traversals were faster than the recall traversals. The time saved on the recall traversal can be attributed to the time spent having to interpret the maps during the guided traversal that is no longer applicable in the recall traversal. In the case of AR, however, the recall traversal took longer. This can be explained by noting that the time to interpret the guidance information is less than the time required to recall the information.

The observation that the time invested in map interpretation resulted in a better recall supports the argument that a better mental map was formed in the process. The mental map was subsequently instrumental in helping users to recall the path when they no longer had a navigation tool to consult. The AR tool, on the other hand, required little cognitive processing and so the mental map created would have been very weak. Thus, when users were asked to recall the path without any navigation tool, more time was required and more errors were made.

Tool Usage

The observation that the AR tool was invoked substantially more than the maps interface indicates that the information from AR did not guide users as far as map information. This is sensible since the AR interface offers immediate route guidance—effectively to the next turn—without additional survey information that would help in a longer traversal. Maps, on the other hand, offer both shorter term travel information as well as longer term survey information. AR guidance on mobile devices would presumably result in pedestrians having to refer to their navigation aids far more frequently. Since the time spent looking at the information per use is significantly lower for AR than for the maps, users may not have to stop while consulting AR information. Indeed, studies such as [59] as well as the Outdoor Navigation Performance study from Chapter 4 support the notion that users tend to use the navigation tools while moving rather than stopping in order to use the tools.

The different interfaces all had similar retention ratios (see Section 5.5.1 for the definition of retention ratios). Since AR was invoked far more than the map tools, this means that the duration of both the references and the retention of the information were proportionally shorter. The need for frequent quick glances at an AR device may not be desirable for reasons of safety, convenience, comfort, and other reasons.

Perceptions of Skills, Usability, and Workload

The correlation between the map comfort question and the SUS scores is surprising at first glance since it indicates that people comfortable with maps (lower scores) will give the navigation tools lower usability ratings. Two more map comfort correlations were surprising: the negative correlation with Guided performance time and the direct correlation with the number of requests made for the navigation tool. Taken together, these three correlations seem to indicate that people who expressed greater comfort with maps rate the usability of the interfaces poorly, take longer than others to navigate through the path with the given navigation tool, and chose to use the navigation tool less than others. While this may seem incongruent, it may speak to the type of people that previously identified as *Traditional Thinkers*, from Chapter 5. These are people who like traditional maps but are less welcoming of technology and tend to use navigation tools less frequently than most. It would seem, from the correlations found here, that they are also potentially less concerned about travel efficiency. This is supported by the fact that the overall correlation between map comfort and SUS was only detected for the AR condition but not for the MP and MY conditions.

The negative correlation of the SBSoD scores with SUS scores is potentially based upon the same logic as the previously noted negative correlation between map comfort scores and SBSoD scores where higher tool proficiency did not indicate a stronger natural sense of direction but the reverse. The negative correlation between SBSoD scores and the TLX combined workload scores may point to the possibility that people with a better sense of direction were able to apply their abilities in the VE and so found the virtual navigation tasks easier.

With respect to the SUS scores, although MP had the lowest average usability score and AR had the highest, the differences were not statistically significant. This was somewhat unexpected since we would have expected that users would find AR to be far more usable than maps. Moreover, the results of the TLX surveys indicated that AR was perceived as requiring significantly more effort than MP in a number of areas. Taken together, these assessments indicate that AR was perceived as a difficult tool, not unlike the results from the Nav2 Navigation Preferences study from Chapter 5 even though AR tracking issues were eliminated. A possible explanation for this is that the administration of the SUS and TLX surveys after the initial Unguided Recall navigation task caused the participants to combine the experiences together. While the Guided navigation may have been seen as easy—and was reflected in the faster time-on-task performance results—the Unguided Recall task was more difficult after using the AR tool. In this way, when asked about perceived effort expended, the response may be to include the challenges encountered in the Unguided Recall navigation task and to form an aggregate opinion of the tool, which is reflected in the score.

The negative correlation detected between SBSoD scores and errors made in the Unguided Recall navigation task is sensible: people with a greater sense of direction will probably make less recall errors given their innate abilities. The negative correlation between the scores from the technology survey and the Guided navigation task time is reasonable since proficiency with technology would likely result in an easier time using a guidance tool.

6.6 Conclusion

This chapter described an experiment conducted in a virtual environment comparing traversal performance and path recall in simulated outdoor pedestrian navigation tasks. The virtual environment allowed us to avoid tracking problems that have plagued AR navigation interfaces in real world experiments and which we believe contributed to sub-optimal performance and perception of AR navigation tools. In this way, we can gain an understanding of how users will behave with AR pedestrian navigation tools in the real world when there is perfect outdoor AR tracking. Our finding that AR does, in fact, yield significant performance benefits, in terms of time-on-task measurement, over north-up maps (without YAH markers) supports our hypothesis.

We also found that AR users had greater difficulties recalling paths, as demonstrated by longer traversal times and greater errors made, which consistent with our hypothesis. While navigation performance is commonly used as a way to judge navigation tools and, in this case, such measurements help us to establish the practical potential of AR navigation tools, our interest in the impact tools have on the formation of route knowledge will require a more direct measure of a tool's cognitive impact. The SUS and NASA TLX surveys provide useful and applicable insights but are fundamentally subjective measures. In the next chapter, we will look at how we may try to establish objective measures that would provide us with insights into the relative cognitive efforts associated with the use of map and AR-based navigation tools.

7

Nav4: Objective Measurement for Ease-of-Use in Pedestrian Navigation Tools

In the last chapter, we saw how simulating perfect tracking in an AR-based pedestrian navigation tool yielded data that supported the assumption that AR would result in faster wayfinding performance than a map-based tool, albeit at the expense of a weaker cognitive map. Presumably, users would be faster with a navigation tool that is easy to use than one that is more difficult to use so—all else being equal—performance can be an indirect measurement of ease-of-use. Of course, ease-of-use is difficult to measure directly and the techniques that are used to assess a tool's usability are usually subjective by nature.

In this chapter, we test our hypothesis more directly by relating ease-of-use with cognitive effort. Specifically, we employ a technique of measuring the cognitive load of a primary task by subjecting the user to a secondary task that competes with the primary task for cognitive resources. By analyzing how a user performs given dual tasks, we can assess how cognitively demanding the primary task is. We designate our study as Nav4 and it relates to research goals RG1, RG2, and RG5 (see Section 3.2) as well as hypotheses H1, H2, and H5 (see Section 3.3).

7.1 Introduction

Although much has been said of the various skills and abilities required for people to multi-task, we often do some very basic multi-tasking without realizing it. Chatting as we take a stroll can be seen as multi-tasking although the acts of talking and walking are hardly considered tasks, natural as they are. It is only when we find ourselves lost as a result of a deep conversation that we realized that we had neglected the wayfinding aspect of our stroll and will now need to devote the greater part of our cognitive abilities to find our way back.

Indeed, any secondary task—be it talking on a phone, texting a friend, or even thinking to ourselves—may compete with the primary task for cognitive resources. In this chapter, we describe a study where we modified SPART to display, in quick succession, words from a pre-defined word list. To read words from the list and commit them to memory requires effort that would otherwise have been devoted to the primary task of navigation. Observing how users performed in a dual task environment will give us insights into how their cognitive resources were taxed and, hence, how they may perceive the ease of use of a given tool.

7.2 Background

While the NASA TLX survey allows us to measure perceived workload effort, the data is subjective by nature. We would like to find an objective way to measure workload effort for map and AR navigation interfaces.

Using a secondary task as a way to monitor the effort required by a primary task has a long history, dating back to the nineteeth century when spring-loaded handles were used to measure grip maintenance [99]. An error in maintaining a constant grip was interpreted as the primary task demanding greater effort.

Owen [66] advocated the use of secondary tasks to probe into the demand of a primary task. Assuming a limit to cognitive resources, degraded performance of a secondary task allows us to track the processing resources consumed by the primary task. In this way, observed changes in secondary task performance can help in determining the processing resources being consumed by the primary task.

Noting that mental workload cannot be detected directly, Novak et al. [64] used a dual-task approach by combining an arithmetic task with a error correction task. Physical measures (e.g, heart rate) were compared with objective (success rate) and subjective (self-assessment) measures. They found that, in a multi-modal interface, the physical measures may not align with subjective results and they noted that designers of context-aware systems should pay particular attention to the potential lack of agreement between subjective and objective meausures. This supports our desire to establish an objective measure for cognitive effort for the use of pedestrian navigation tools.

In order to create a secondary task appropriate for our testing platform, we build on top of the work undertaken by Green and Helton [23], who studied how climbers were affected by having a secondary task of memorizing words from a carefully constructed word list. We adopt a similar secondary task and use the same word list where the chosen words were selected by their syllable count, letter count, and meaningfulness, amongst other factors [67].

7.3 Study Design

The study of this chapter was built upon SPART, as described in Chapter 6 and the reader is referred to Section 6.3 for details of the hardware and software setup for the study. Here, we describe the modifications made to this earlier work to accommodate the current study.

7.3.1 Modifications to SPART

SPART was modified to periodically display a word, from a pre-defined word list, in the upper left hand corner of the screen, as shown in Figure 7.1. The same word list was used for the different interface conditions.

In the previous chapter, the results from the MP condition were more pronounced than the results from the MY condition but were otherwise similar (see Section 6.4) so we streamlined the study by omitting the MY condition. This allowed us to focus on the expected effect.

Figure 7.1: Words are shown in the upper left hand corner of the SPART virtual environment to distract the user.

7.3.2 Environment

The reader is referred to Section 6.3.1 for a general description of the virtual environment used in the study. To further streamline the study, we retained Path A but dropped Path B, since the results from the two paths were substantially the same.

7.3.3 Procedure

The demographics and training procedures remain unchanged from the description given in Section 6.3.2. Once the training was completed, the experimental trials proceeded as follows:

- **Navigation Task 1:** First, the participant was asked to navigate through the virtual environment by following the guidance provided by the given navigation tool. At the same time, they were asked to memorize as many of the displayed words as possible and ignoring the nonsensical words.

- **Secondary Task Measure:** Next, the participant was asked to list as many of the words they had seen as possible in two minutes. The interface provided an option to terminate the exercise early if they felt they were unable to recall any more words in the given time.

- **Navigation Task 2:** Finally, the participant was returned to the starting point of the path just completed and asked to navigate through the same virtual environment, following the same path previously traversed, but without the use of a navigation tool. There was no secondary task in this traversal since we are interested in how well they can recall the path based upon their earlier distracted navigation.

The participants were given a chance to make some comments as well as answer some subjective questions through a web-based form about the ease-of-use, navigation cues used, and other issues as shown in Appendix D.

7.3.4 Technology

Our system was deployed on standard desktop computers using Intel i5-3470S processors with 16 gigabytes of RAM with standard keyboard and mouse input devices. Each computer was attached to a 21-inch flat-screen monitor which accommodated a resolution of 1920x1080. Unlike the deployment used in the experiment described in Section 6.3.3, the virtual environment was installed and executed on the local machine and so the internet transmissions were limited to data transfer of usage data. The user experience remained unchanged since the previous deployment had pre-downloaded all the assets.

Software

With the exception of the addition of a secondary task, described below, this study used SPART, as described in Section 6.3.4.

For the secondary task, we used the standardized word list from [23] (see Appendix I) of 60 words that was supplemented by an additional 18 recognizably nonsensical strings of characters. The nonsensical strings were included in keeping with the methodology used in [23]. Participants were asked to memorize the recognizable words but to ignore the nonsensical strings, which were generally collections of consonants that were obviously not English words, such as *llxgrrc*.

All participants were given the same randomly ordered list of words. We allocated a five second window for each word to be displayed. Within each five second window, each word had a predetermined delay of between zero and three seconds before it was displayed for two seconds. The delay amount was randomly generated but fixed for all participants.

7.3.5 Data Collected

The same subjective and objective data was collected, as described in Section 6.3.4 and, in addition, the number of correct words recalled in the secondary task as well as the amount of time used to recall the words were recorded.

7.4 Results and Analysis

We begin this section by examining the results for the dual task study. We then compare our results here with the single task results from Chapter 6. Since we used the same SPART experimental environment, we were able to compare the two studies to better understand how the navigation tools and their users were affected by the secondary task.

7.4.1 Participants

A total of 49 participants (25 female) ranging in age from 18 to 43 years old (M=26.29, SD=6.26) completed the study. Recruitment was primarily through on-campus means and so the majority of participants were students. A voucher worth $5 and redeemable at one of the university campus cafes was given as compensation for participation, which generally took between 30 and 45 minutes. A boxplot analysis of the time-on-task completion times detected two extreme outliers whose completion times were more than three standard deviations from the mean. The two outliers were removed for the analysis leaving 47 valid samples.

7.4.2 Dual Task Results

We begin by providing an overview of how the participants performed in the dual task environment. We then present an analysis of the data followed by some observations.

Overview

Overall, participants took more time to traverse the paths when using a guidance tool ($M = 212.68s, SD = 85.39s$) than when recalling the path from memory ($M = 187.76s, SD = 31.27s$), as shown in Figure 7.2(a).

With respect to accuracy (measured by the number of wrong turns made), Guided users made fewer errors on average ($M = 1.21, SD = 2.01$) than Unguided users recalling the paths from memory ($M = 2.83, SD = 1.95$), as shown in Figure 7.2(b).

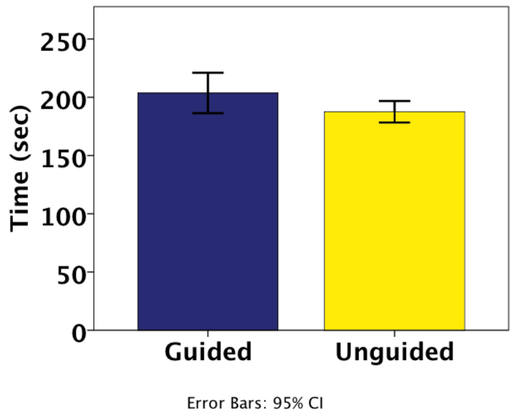
In the secondary task of memorizing words, AR users recalled a greater number of words on average ($M = 6.41, SD = 4.19$) than Map users ($M = 4.09, SD = 2.52$). AR users also spent more time recalling the words ($M = 93.00s, SD = 29.74s$) than Map users ($M = 71.14s, SD = 31.89s$). These are shown in the graphs of Figures 7.2(c) and 7.2(d).

Time Performance Analysis

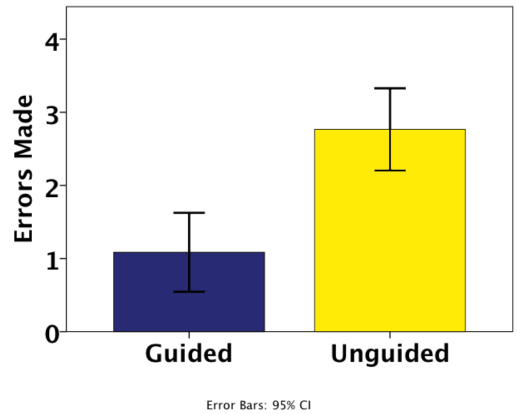
We conducted a 2 (guidance: Guided vs. Unguided) by 2 (interface: Map versus AR) mixed ANOVA for both travel times and travel accuracy. The slower travel time for Guided users compared to Unguided users, as noted above, was significant ($F(1, 47) = 5.67, p < .05$). There was also a significant interface*guidance interaction for travel time, ($F(1, 47) = 19.19, p < .001$), However, there was no significant travel time main effect for interface, ($F(1, 47) = .17, p = .68$).

Regarding accuracy, the greater accuracy (fewer wrong turns) exhibited by Guided users as compared to Unguided users, as noted above, was significant, ($F(1, 47) = 22.77, p < .001$). However, there was no significant travel accuracy difference between the interfaces, ($F(1, 47) = 1.70, p = .20$.) although there was near significance detected for interface*guidance interaction for accuracy, ($F(1, 47) = 3.89, p = .055$).

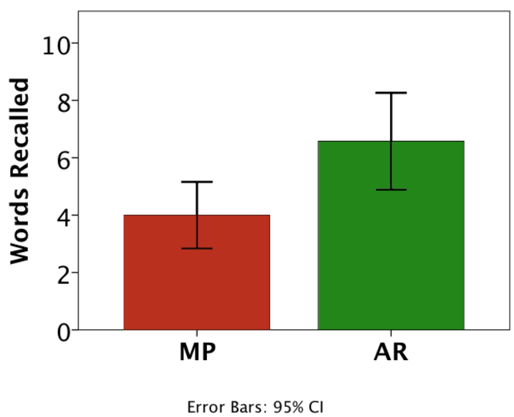
Given our *a priori* expectations, we conducted follow-up comparisons by conducting



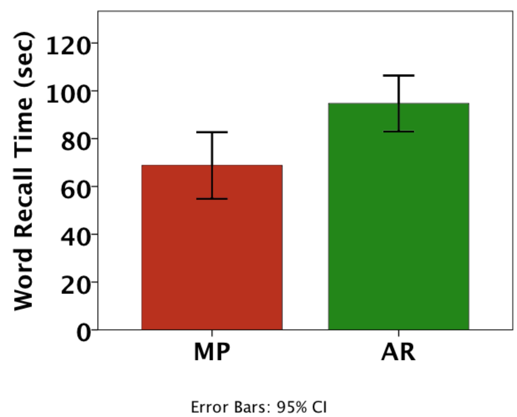
(a)



(b)



(c)

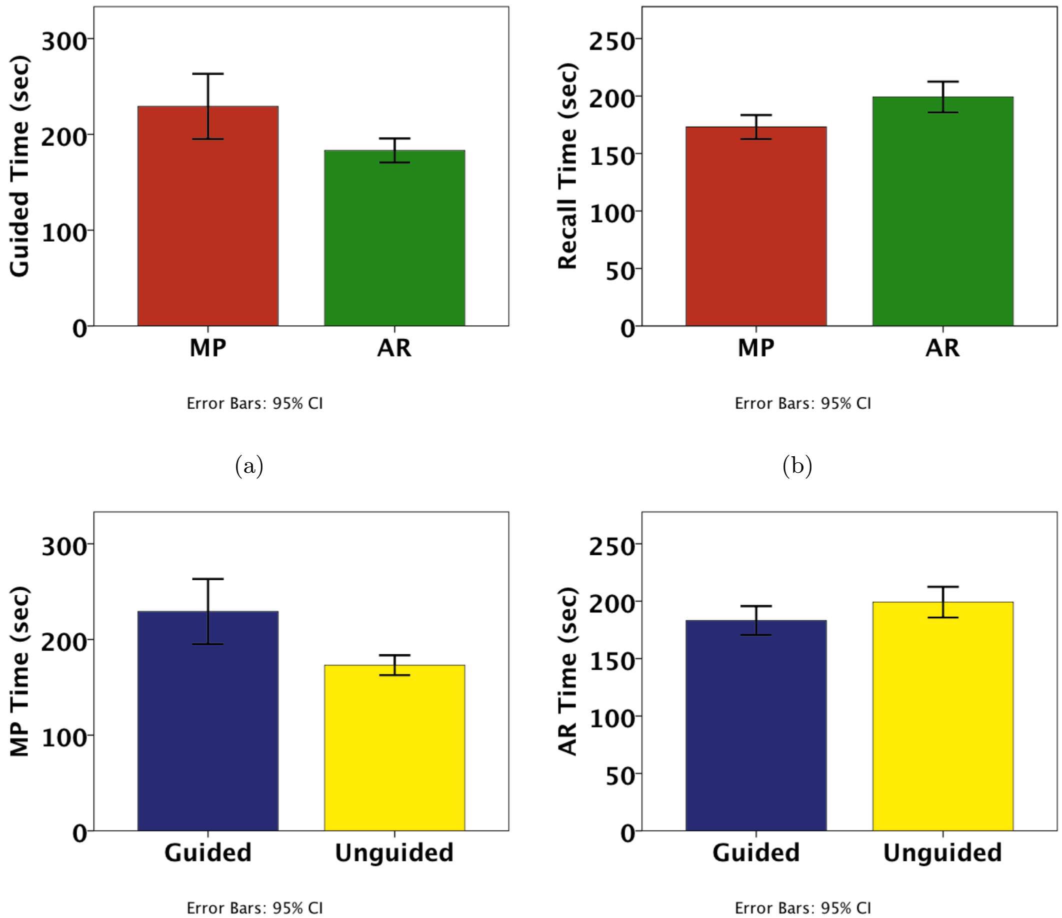


(d)

Figure 7.2: Overview of dual task data including traversal time, accuracy (errors made), and word recall performance.

T-tests on the differences in travel time and accuracy for the interfaces for each traversal. Guided Map users ($M = 247.63, SD = 113.11$), when compared to Guided AR users ($M = 192.34, SD = 56.91$), had significantly slower traversal times ($t_{47} = 2.22, p < .05$). For Unguided travel, however, Map users ($M = 174.30, SD = 23.05$) were, when compared to AR users ($M = 214.0107, SD = 83.01$), significantly faster ($t_{47} = 2.15, p < .05$). This is shown in Figures 7.3(a) and 7.3(b).

Comparing Guided and Unguided modes within each interface, Map users were signifi-



(a) (b)

(c) (d)

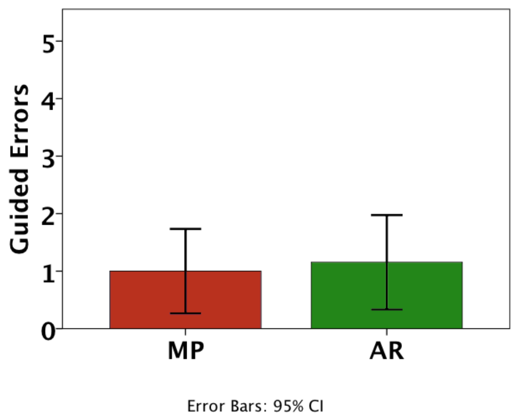
Figure 7.3: Navigation tool usage.

cantly faster in the Unguided mode than in the Guided mode ($t_{47} = 2.98, p < .001$) and a large effect size was seen (Cohen's $d = .90$). AR users, however, did not exhibit any significant differences in time between Guided and Unguided navigation ($t_{47} = 1.11, p = .271$). These are shown in Figures 7.3(c) and 7.3(d).

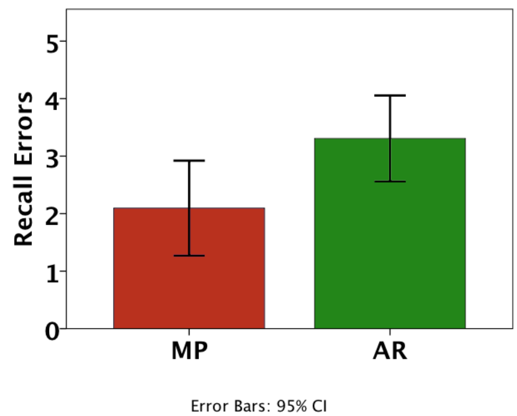
Accuracy Analysis

Comparing Guided Map users ($M = 1.27, SD = 2.028$) with Guided AR users ($M = 1.22, SD = 2.025$), no significant differences in the number of wrong turns were detected

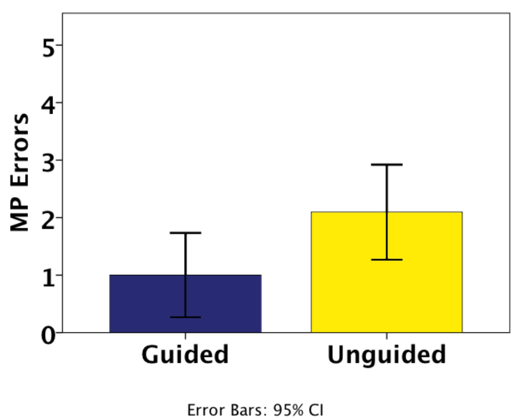
($t(47) = .087, p = .93$). For Unguided Recall traversals, the number of errors made by Map users ($M = 2.27, SD = 1.96$) was, compared to AR users ($M = 3.63, SD = 2.47$), significantly lower ($t(47) = 2.097, p < .05$).



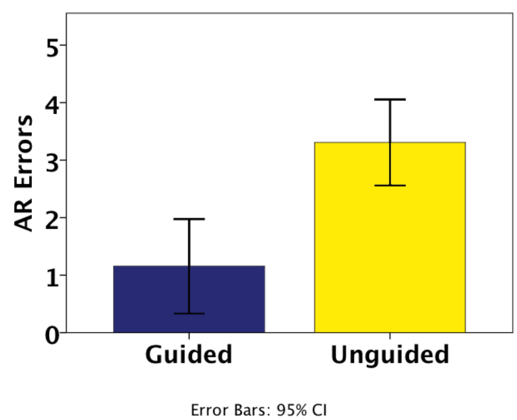
(a)



(b)



(c)



(d)

Figure 7.4: Navigation tool usage.

No significant differences were detected in accuracy for Map users between Guided and Unguided Recall navigation ($t(47) = 1.67, p = .103$). A large effect size was observed for AR users (Cohen's $d = 1.066$), who were signficantly less accurate in the Unguided mode than in the Guided mode ($t(47) = 3.92, p < .001$). This is shown in Figures 7.4(c) and 7.4(d).

Secondary Task Analysis

We examined the secondary task results with T-tests and found that the recall of words was significantly better for AR users than for Map users, $t_{47} = -2.28, p < .05$. Significantly more time was also taken by AR users than by Map users, $t_{47} = -2.48, p < .05$.

7.4.3 Single-Task and Dual-Task Comparative Analysis

As a between-subjects study, we were able to compare the data from the experiment described in this chapter with the experiment described in Chapter 6, provided we cull the Nav3 data in order to restrict our comparisons to be between participants under the same experimental conditions. Specifically, from the SPART study of Chapter 6, only users given the MP and AR interface conditions (omitting the MY condition) and who traversed Path A first were used in the analysis in this section. This yielded 22 participants of the 71 participants from the SPART study who qualified for consideration in the analysis here. The participants were evenly divided between the interfaces—i.e., there were 11 MP users and 11 AR users.

Dual Task Time Performance Analysis

We conducted a 2 (guidance: Guided vs. Unguided) by 2 (interface: Map versus AR) by 2 (task: single vs. dual) MANOVA for travel times. No significant three-way interactions were detected ($F_{1,134} = 1.65, p = .20$). There was a statistically significant ui*guidance interaction ($F_{1,134} = 7.53, p < .01$), as observed in Section 7.4.2, but statistically significant interactions were not detected for ui*task, ($F_{1,134} = .74, p = .39$) nor for task*guidance ($F_{1,134} = .23, p = .63$).

As before, based upon our *a priori* expectations we conducted follow-up comparisons for each traversal. Map users had significant differences in travel times between the Guided single-task ($M = 187.25s, SD = 16.88s$) and dual-task ($M = 247.63s, SD = 113.11s$) modes ($t_{31} = -1.75, p < .05$). Significant differences were also found between the Unguided single-task ($M = 155.52s, SD = 15.14s$) and dual task ($M = 174.30s, SD = 23.05s$) modes ($t_{31} = -2.44, p < .05$). This is shown in the graphs of Figures 7.5(a) and 7.5(b).

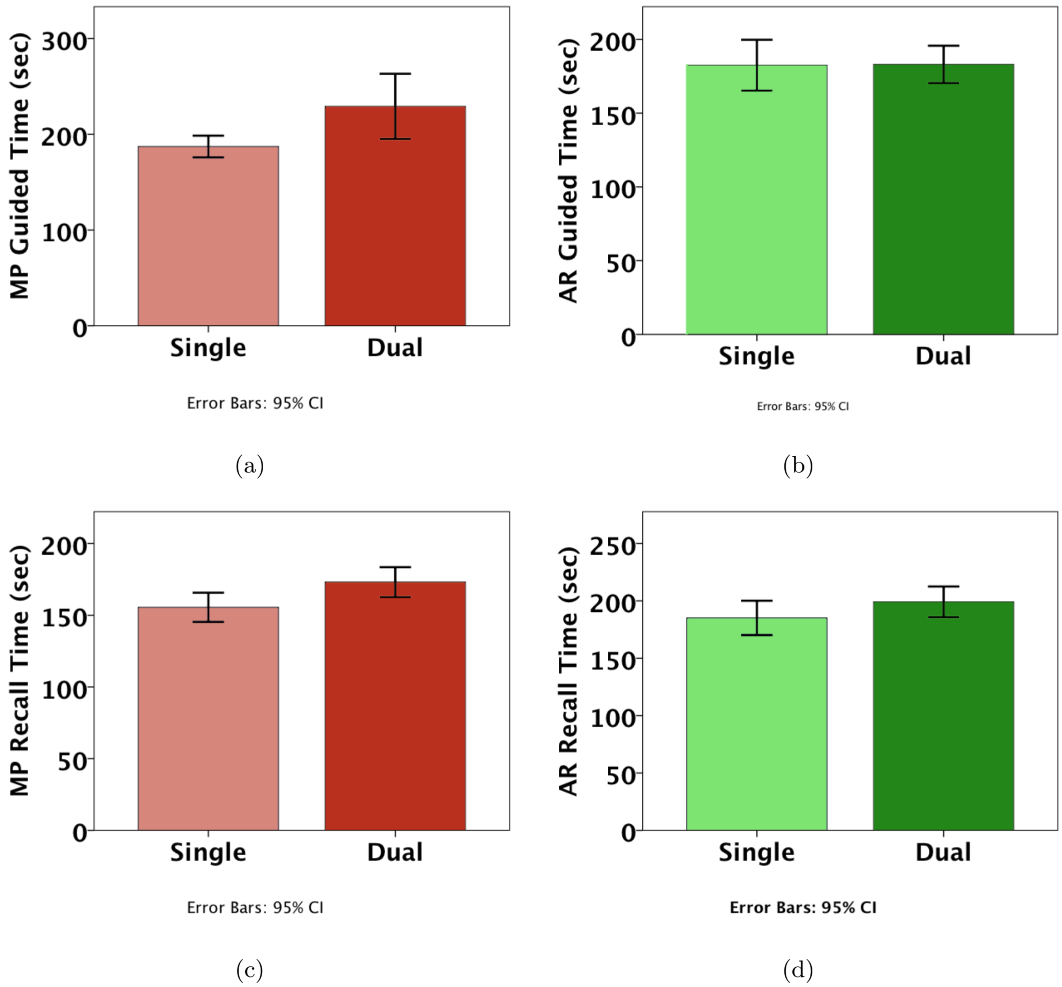


Figure 7.5: Single and Dual-task comparisons.

AR users did not exhibit any significant differences in travel time between Guided single-task ($M = 182.53s, SD = 25.67$) and dual-task ($M = 192.34s, SD = 56.91s$) modes ($t_{36} = -.546, p = .59$) nor between Unguided single-task ($M = 185.17s, SD = 22.28s$) and dual-task ($M = 214.01s, SD = 83.81s$) modes ($t_{36} = -1.12, p = .27$). These are shown in the graphs of Figures 7.5(c) and 7.5(d).

Dual Task Accuracy Analysis

A similar 2x2x2 MANOVA was conducted for travel accuracy as was done for travel time. No significant three-way interactions were detected ($F(1,134) = .97, p = .33$). There was a statistically significant ui*guidance interaction ($F_{1,134} = 8.70, p < .01$), as observed in Section 7.4.2, but statistically significant interactions were not detected for ui*task ($F_{1,134} = 1.11, p = .29$) nor for task*guidance ($F_{1,134} = .23, p = .63$).

Follow-up comparisons were once again carried out for each traversal based upon a priori expectations. No significant differences were detected for erroneous turns for any of the conditions, as summarized in Table 7.1.

	Single	Dual	t_{31}	p
Guided MP	$M = .36, SD = .67$	$M = 1.27, SD = 2.03)$	-1.90	.067
Recall MP	$M = 1.00, SD = 1.48$	$M = 2.27, SD = 1.96$	-1.90	.067
Guided AR	$M = .36, SD = .92$	$M = 1.22, SD = 2.03$	-1.90	1.00
Recall AR	$M = 3.82, SD = 2.32$	$M = 3.63, SD = 2.47$	-1.90	.93

Table 7.1: ***Comparison of errors made in single- and dual-task modes***

7.4.4 Subjective Data

The SUS and combined TLX results are shown in Tables 7.2, left and right, respectively. A t-test conducted on the Dual task SUS results detected no significant differences between Map and AR ($t_{44} = .77, p = .44$). A t-test conducted on the Dual task TLX results indicated that AR users perceived a significant higher workload than Map users ($t_{45} = -2.077, p < .05$).

Comparisons were also made between Single and Dual task participants (from Nav3 and Nav4 studies, respectively). Significant differences in SUS results between Single and Dual task participants were detected for neither Map users ($t_{28} = .23, p = .82$) nor AR users ($t_{34} = .40, p = .69$). Similarly, significant differences in TLX results between Single and Dual task participants were detected for neither Map users ($t_{30} = .35, p = .077$) nor AR users ($t_{35} = .092, p = .93$).

SUS				
	Single		Dual	
	Mean	SD	Mean	SD
Map	36.70	8.88	35.80	10.64
AR	34.90	8.84	33.54	9.21

TLX				
	Single		Dual	
	Mean	SD	Mean	SD
Map	6.86	2.22	8.19	2.56
AR	9.97	2.55	9.50	1.75

Table 7.2: SUS (left) and TLX (right) data for Single and Dual tasks

7.4.5 User Comments

As with the Nav3 experiment, users were asked the following questions to help understand how they remembered the path they were navigating and to give feedback about the interface:

1. Did anything help you to remember the path?
2. What was frustrating about the computer interface?
3. Did the simulation capture reality?

We collected usable responses from 26 of the subjects. In terms of things that were used to remember the path travelled along, 14 people said that they used street signs, 16 used buildings or landmarks, and only 3 said that they remembered the sequence of turns they were making. This is similar to the results in chapter 6 where people also responded with street signs and buildings being the most widely used navigation cues. Of the responses, 11 people also mentioned using both street signs and buildings together. For example, one person said "Buildings, including what they were eg church and towers and what they looked like from my vantage point. Also street sign recognition to guide me back." Another said "Some street signs and landmarks like the cathedral and the Petronas towers." Users also combined street sign recognition with remembering the turns made. For example, one subject wrote "A few street signs, but generally I remembered which way to turn and after how many streets." This suggests that people often use several navigation cues to help them recall the path travelled over.

When asked what was frustrating about the experience, 5 people mentioned the slow speed of walking, 3 people did not like the mouse viewpoint control method, while 6 people thought there was nothing wrong with the interface. There were only a couple of comments made about the added difficulty due to the word memory task. One user saying "The words being displayed being in the top left corner, took my eyes away from all the was happening on the path, so buildings and road signs., and another "There were a lot of words to remember during the secondary task phase." There were also some complaints about the navigation cues or lack of them. One person complained about having "...no marker that shows where I am at the moment..." and another noted that "the pink line would cover up the street name, and for it to pop up instead of stop you from moving due to short term memory." These results are a little different from those from chapter 6 in that the proportion of people reporting that the walking speed is too slow is much lower, but this might be because people were too focused on the memory task to notice navigation speed.

When asked if the simulation captured reality, 13 people provided answered that were neutral ("slightly similar") to very positive ("Very closely"), while only 3 people thought that it was not like reality ("not really"). In this case there were a number of comments about how walking while performing a word memory task was unnatural. For example, "I felt that since I was told that words would be shown in the upper left I focused on that rather than the path. In the real world I would be more likely to focus on where I was going." Another person said "Pretty close. But if it hadn't been for the words that I knew I was supposed to remember, I would have remembered the path much better. They distracted me from following the route." This was clear evidence that although the users felt that the environment was realistic, the dual task was indeed distracting them from noticing their surroundings.

After completing the user study, subjects were able to submit their own comments about the experience. As expected participants noted that trying to remember the words in the dual task impacted their ability to learn their surroundings. For example, P17837, an AR participant, said, "...if it hadn't been for the words that I knew I was supposed to remember, I would have remembered the path much better. They distracted me from following the route." P58, a map user, noted that the words "displayed being in the top left corner, took my eyes away from all that was happening on the path...buildings and road signs." Finally, some people did not even think to learn their surroundings. As P17843, an AR user, said, "I didn't even think about looking at the building types or street signs until [the] final challenge. I was too busy remembering the words, It didn't occur to me to remember my surroundings."

It should be noted that the need to remember the surroundings was not revealed to any participants prior to the Guided traversal and so it is unclear if the lack of a secondary task would encourage that (although the existence of one would certainly discourage from it).

People also commented on how the simulation did not reflect the real world. Subject P17812, a map user, observed, with regards to the capture of reality: "...no traffic and/or pedestrians makes it rather unrealistic and artificial." While P17813, an AR user, noted that getting the correct path by "trial and error did not reflect reality."

Some subjects also relied more on the simulated cues in the environment rather than the buildings or other landmarks to aid their navigation. AR user P67 said that the AR guidelines on the road tended to "drag away my sight from looking at the buildings" and thought that "it might help me remember the buildings better if they are placed at the height of my view." Map user P68 noted that "After realizing the cone will help me each time I took a wrong turn, I started to not pay attention as hard about where I was going but relied on the cone as trial and error." This participant was removed from the analysis as an outlier because the Guided traversal time was over three standard deviations from the mean.

These comments show that the dual task was effective in providing a distraction from the user surroundings, but that the virtual environment could have been more realistic. They also indicate that people were depending on the AR cues shown rather than trying to build their own mental model of the urban space.

7.5 Discussion

Our main goal in this study was to better understand how a secondary task would affect a pedestrian using a navigation tool for a targeted wayfinding task. In particular, we were interested in seeing how Map and AR users would be affected by such a distraction and if the navigation task would suffer, the secondary task would be poorly executed and/or if the recall of the route would be impacted. Our initial single-task study, as described in Chapter 6, established that Map users and AR users took statistically the same amount of time when using the navigation tool for guidance in Path A while Map users took significantly longer than AR users on Path B. We also saw that Map users were significantly faster on the recall task. With a dual task, we found that, despite using Path A, Map users took significantly longer to find their way in the guided mode than dual-task AR users, who experienced no significant change in performance. This may indicate that the secondary task had a substantial impact on Map users while it did not practically affect AR users. A possible explanation for this is that Map users had to split their cognitive resources between two tasks that were in competition. The AR condition, on the other hand, may require so little cognitive effort from the user that a secondary task demanding attention would easily receive the necessary attention without diminishing the performance of the primary task of navigation. Users in the real world are often engaged in some secondary task—such as chatting with a friend—while finding their way in an urban environment, so the potential of AR-based navigation tools in effectively guiding such users without diminishing their secondary task is attractive.

While the secondary task slowed down Map users significantly, the significant drop in travel time for Map users between Guided and Unguided states indicated that much of the time spent in the Guided mode was devoted to interpreting the map, as was the case for the single-task Guided traversal. The secondary task did not, however, diminish the retention of a mental map for Map users since they were still significantly better than AR users in Unguided travel time performance as well as in Unguided accuracy. This may suggest that the implicit retention of a mental map did not suffer as a consequence of having a secondary task. In other words, the secondary task increased the amount of time the user needed to accomplish the primary task but it did not affect the mental map created.

With respect to the secondary task, AR users were able to recall significantly more words than Map users without significantly increasing their Guided traversal times from their single-task traversal. Map users, on the other hand, not only recalled significantly less words than AR users but also took significantly longer to follow the Guided traversal when given a secondary task. As previously observed, this seems to point to the possibility that AR users had a greater capacity than Map users to devote cognitive resources to the secondary task without suffering in the primary task.

Perceived usability and effort (SUS and TLX, respectively) did not change significantly between the Single task and Dual task traversals. This probably means that the secondary task did not overwhelm users enough to impact upon their perception of the interface or the effort they had to exert. Between interfaces, the perception for Dual tasks also remained unchanged from the Single Task: no significant differences were found between Map and AR users for SUS but, for TLX, AR users again indicated that AR required significantly more effort than Maps. Like the Nav3 result, this suggests that the difficulties AR users had in recalling the traversals made the combined tasks (of Guided and Unguided Recall traversals) appear more difficult to them than to Map users.

7.6 Conclusion

Using SPART, as described in Chapter 6, we investigated how distracted pedestrians would perform in navigation tasks. Using a secondary task of word memorization, we were able to measure the degree to which the primary navigation task suffered. We found that Map users suffered greatly in the navigation task and were less able to remember words than AR users.The time-on-task performance of AR users remained statistically unchanged between single and dual task navigation. We attributed this to the greater cognitive demands associated with using maps. This suggests that maps may be more demanding to use than AR, associating them with lower ease-of-use when compared to AR. We also found that map users continued to have significantly better route recall than AR users, both in terms of performance and accuracy, when given a secondary task.

Given that AR users were significantly faster than Map users, even with a secondary task, we are now interested in the possibility of using part of the time saved by AR users and devote it to improving route knowledge, so that the benefit of faster traversal would not be negated by a substantial degradation of spatial knowledge. We will explore this in the next chapter, where our final study will use SPART to provide users with an AR-based navigation tool that attempts to improve user's spatial awareness.

8

Nav5: An Interface for Balancing Navigation Efficiency with Spatial Knowledge Acquisition

In the previous two chapters, we saw that AR-based wayfinding guidance can improve time-on-task performance and does so in a manner that is less taxing on cognitive resources when compared to map-based wayfinding guidance. Taken together, we regard this as an opportunity to find a solution that could be used to improve spatial knowledge acquisition without sacrificing navigation performance. In this chapter, we present our final study, which is based on a proposed interface that attempts to extend an AR-based navigation tool by including interaction elements designed to improve path recall. In this way, a user can benefit from more efficient navigation while strengthening route knowledge that may otherwise be diminished when is navigation accomplished with too little effort. We refer to this study as Nav5 and it relates to research goal RG6 (see Section 3.2) and tests hypothesis H6 (see Section 3.3).

8.1 Introduction

Our analysis of the savings in performance from Chapter 6 and lower cognitive demands from Chapter 7 provides us with a potential opportunity to creatively utilize the available time and cognitive resources to help the user improve spatial knowledge. Many possibilities exist and, in this chapter, we present one potential solution that attempts to balance navigation efficiency with spatial knowledge acquisition by exploiting the time saved by using AR technology. Given the human interaction nature of this thesis, we are also interested in gaining insights into the usability of any such solutions.

While a wide variety of solutions may be possible, we want to ask: will users accept an attempt to increase their workload in the name of improving spatial knowledge? This is not an easy question to answer. The notion of usability is not as objective as time-on-task performance measures or the comparison of cognitive loads made apparent by imposing dual task. However, we can get a sense of the parameters that govern the design of features we wish to—for lack of a better word—enforce upon the user by studying usage behavior in response to such additional features. In this way, we can try to find some more general design principles that can help guide us in the creation of pedestrian navigation tools that seek to balance wayfinding efficiency with formation of cognitive maps.

8.2 Background

As we saw in Chapter 2, arguments have been made that greater user effort in the navigation process may help to improve spatial knowledge [10][30]. We described how Parush et al. [68] withheld constant directional information and used random orientation quizzes to strengthen a user's spatial awareness but noted that the significant differences found in spatial knowledge acquired based upon relative direction tests may be more of a direct reflection of the use of orientation quizzes than true acquired spatial knowledge. The authors observed that, from a practical perspective, it might not be wise to expect that users would want to subject themselves to random—if occasional—orientation quizzes. In this chapter, we will want to address such concerns.

Our review also covered the study by Waters and Winter [97] which also withheld constant orientation from the user but instead of random quizzes, provided landmark cues to help improve spatial awareness. There is general agreement that landmarks are effective tools for navigation guidances [27][3][54] and so this is a sensible and less intrusive approach. Unfortunately, because the study was not based upon an interactive navigation task where the user could become lost, no significant results were achieved.

In this chapter, we take the promising aspects of the studies cited above and address the shortcomings to create an interface that we hope would not only yield significant results but also provide insights as to how we may appeal to users on a practical level.

8.3 Study Design

Using the studies cited in the previous section to inform the design of our interface, we chose to use an active navigation task through a virtual environment rather than a passive viewing of route videos and to use landmark cues instead of orientation quizzes. We preferred the approach of engaging users with active interaction over passive landmark cues and so we created landmark quizzes. However, we didn't want to diminish usability by presenting cues for improving spatial knowledge at random times, so we integrated them into the navigation request process. A power analysis based upon the observed effect size of .18 from the SPART study of Chapter 6, indicated that we would need 303 participants in order to achieve a power of 80%. Consequently, in the interest of securing a large number of participants, we also deployed our study over the internet.

We used our SPART system, as described in Chapter 6, to generate an internet version of the virtual city simulation. The reader is referred to Section 6.3 for details regarding the conditions and technologies of the original study. Here, we describe the modifications made to accommodate the current study.

All map-based interfaces were removed from SPART and replaced with three AR-based interfaces, each featuring two modes: Simple and Work. In the Simple Mode, the AR path was immediately shown in response to a request for navigation guidance. In the Work Mode, a "landmark quiz" was first given. In the landmark quiz, an AR 3D wireframe box is rendered around a particular landmark at or near the upcoming intersection. Three images are displayed near the bottom of the interface, each with a close-up image of a building façade. The participant needs to select the façade that corresponds to the highlighted building. This is shown in Figure 8.1. An error message is displayed if the selection is wrong and the participant is free to choose again. When the correct image is selected, the AR path is displayed to guide the user. The two modes are shown in Figure 8.2.

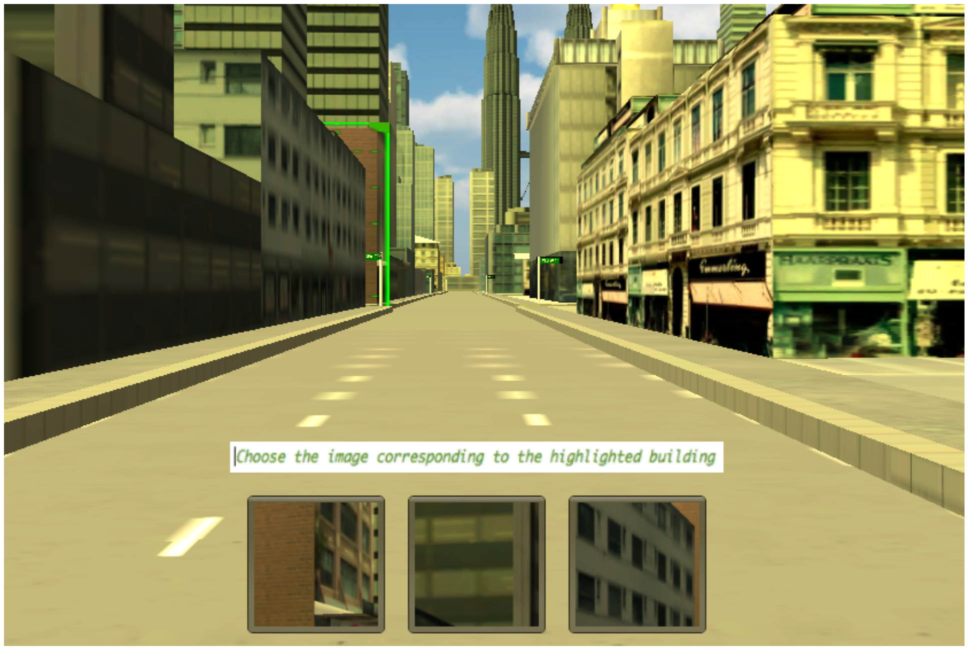


Figure 8.1: In the eAR and reAR navigation tools, participants are shown three images and a highlight box around a building at or near the upcoming decision point. The correct image has to be chosen before the navigation direction is revealed.

Because of concerns over retaining participants on-line (who may abandon the study if it takes longer than they have the patience for) we wanted to minimize the time of the study and so we only used one path (Path A) of the original environment (see 6.3.1). Each of the seven straight segments of the path was divided into two zones, the Basic Zone followed by the Effort Zone (see Figure 8.3). The boundaries dividing the Basic Zones from the Effort Zones were determined by manual observation: Effort Zones began at a point where a pedestrian, positioned at that distance from the upcoming intersection where a turn was to be made, can see landmarks situated at the intersection.

Three interface conditions tested in the study were based upon how navigation tool requests were handled in the Effort Zones, as shown in Figure 8.4:

- **Basic (AR)** used Simple Mode in the Effort Zone (i.e., showed the directional path immediately upon request)
- **Effort (eAR)** used Work Mode for first tool request in the Effort Zone, then Simple

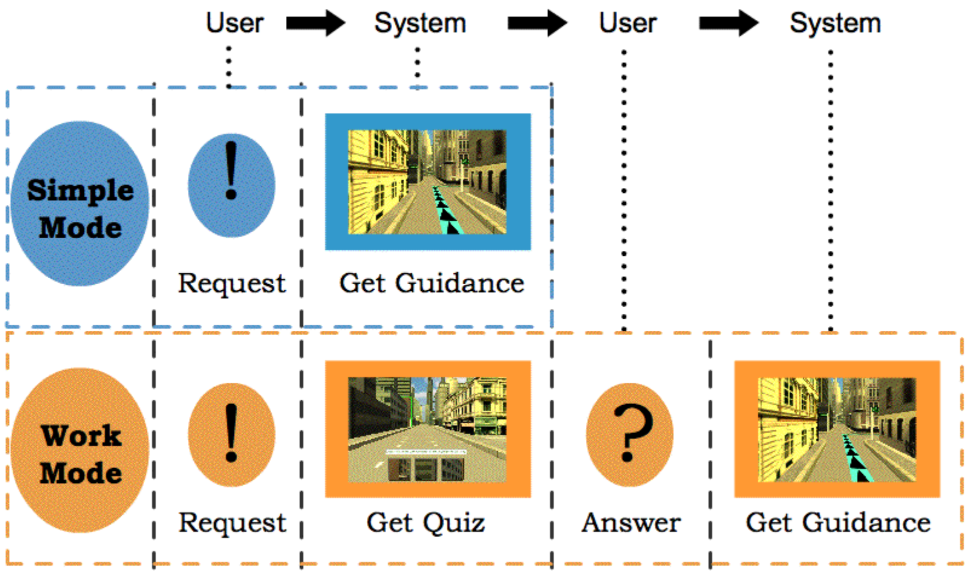


Figure 8.2: The two navigation tool modes.

Mode thereafter (i.e., imposes a landmark quiz the first time the navigation tool is requested in the Effort Zone)

- **Repeated Effort (reAR)** used Work Mode for every request in the Effort Zone (i.e., imposes a landmark quiz every time the navigation tool is requested in the Effort Zone)

Two effort conditions were created so that we could gain insights into both the impact such features may have on improving spatial knowledge as well as the limits of usability that are acceptable since having a landmark quiz for each navigation tool request may be considered too intrusive by users who simply want guidance information passively.

8.3.1 Procedure

The demographics and pre-test questionnaires remain unchanged from the study procedure described in Section 6.3.2. The training procedure was made more robust since this study was deployed on-line and took place remotely. Instead of an abstract 3D environment of cubes, another part of the virtual city was used to familiarize users with the actual setting. A more developed guidance narrative was created for the training phase so that users were required to experience all the relevant interactions—including wandering off too far so as to

Figure 8.3: The path is divided into seven segments, the first six of which are then subdivided into Basic (blue) and Effort (gold) zones. Requests for directions would be immediate in the Basic Zones but may be preceded by a landmark recognition quiz in the Effort Zones.

collide with the buildings—in order to minimize confusion during the actual experimental trials.

Two full traversals were required: a guided trip through the path followed by an unguided trip through the same path. Post-test questionnaires included the SUS and TLX surveys as well as the opportunity to leave comments through a web-based form.

Unlike the previous studies done with SPART, this study was designed to be deployed online as a web-based application so that remote participation would be possible. Since candidates from previous studies were not allowed to undertake this study (they will have

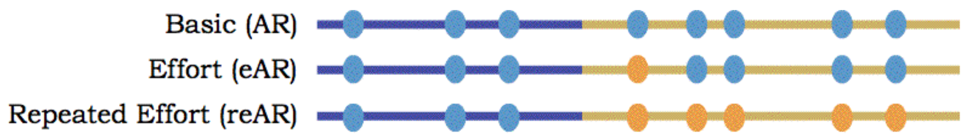


Figure 8.4: The experimental conditions: purple line=Basic Zone, tan line=Effort zone; blue dot = Simple Mode, gold dot = Work Mode.

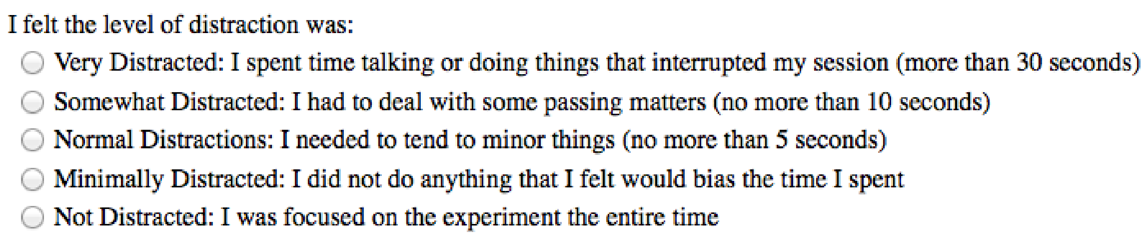

I felt the level of distraction was:
- Very Distracted: I spent time talking or doing things that interrupted my session (more than 30 seconds)
- Somewhat Distracted: I had to deal with some passing matters (no more than 10 seconds)
- Normal Distractions: I needed to tend to minor things (no more than 5 seconds)
- Minimally Distracted: I did not do anything that I felt would bias the time I spent
- Not Distracted: I was focused on the experiment the entire time

Figure 8.5: On-line participants were asked to self-assess the level of distraction they felt were relevant after they had completed the study. Only data from "Minimally distracted" and "Not distracted" were retained for analysis.

been exposed to the nature of the study and the configuration of the virtual city) and we had practically exhausted the local network of potential participants, a web-based version of the study was created. The post-test survey included a 5-option multiple choice question asking about the level of distraction the participant felt was applicable during the study, as shown in Figure 8.5. Due to the lack of direct oversight in an on-line study, we discarded all data where the response to the distraction question was "normal" or above. Only data associated with a distraction level of "None" (no distractions) or "Minimally distracted" (not enough to bias timing) were retained for our analysis.

8.4 Results and Analysis

In this section, we present the results and analysis of the data from the study including the objective data (performance, accuracy, and navigation tool usage), subjective data (self-assessment of map and technology proficiency, sense of direction survey as well as perceived usability and workload surveys), feedback from participants.

8.4.1 Participants

A total of 211 participants registered for the study but only 78 participants (36 females; mean age=32.67, SD = 11.29) successfully completed the study. Deployment of our study over the internet in a manner that was accessible via web browser allowed us to reach a wide audience but such an approach also faced many challenges and Table 8.1 summarizes the attrition of participants.

Participation Phase	**N**
Sign up	211
Pre-test survey	211
Had (or installed) Unity3D web player	112
Finished Simulation	105
Not influenced by distractions	78

Table 8.1: ***Attrition of participants recruited***

99 participants did not proceed past the point where the Unity3D web player was needed, presumably because the installation of the browser plugin set too high a barrier for them to complete. Of the 105 participants who completed the study, 27 indicated a distraction level of 2 ("normal") or above and so were discarded from the analysis. This left 78 participants who contributed acceptable data. A boxplot analysis of the time-on-task completion times detected two extreme outliers whose completion times were more than three standard deviations from the mean. The two outliers were removed leaving 76 valid samples.

8.4.2 Performance Results

Guided Traversal

There were no significant differences in performance times between the three conditions. Users of AR had the lower mean time-on-task for traversing the guided path ($M = 333.15s, SD = 80.17s$). Users of eAR had a higher mean time-on-task measure ($M = 368.76s, SD = 78.97s$) and users of reAR had the highest values ($M = 379.51s, SD = 68.85s$). This data aligned

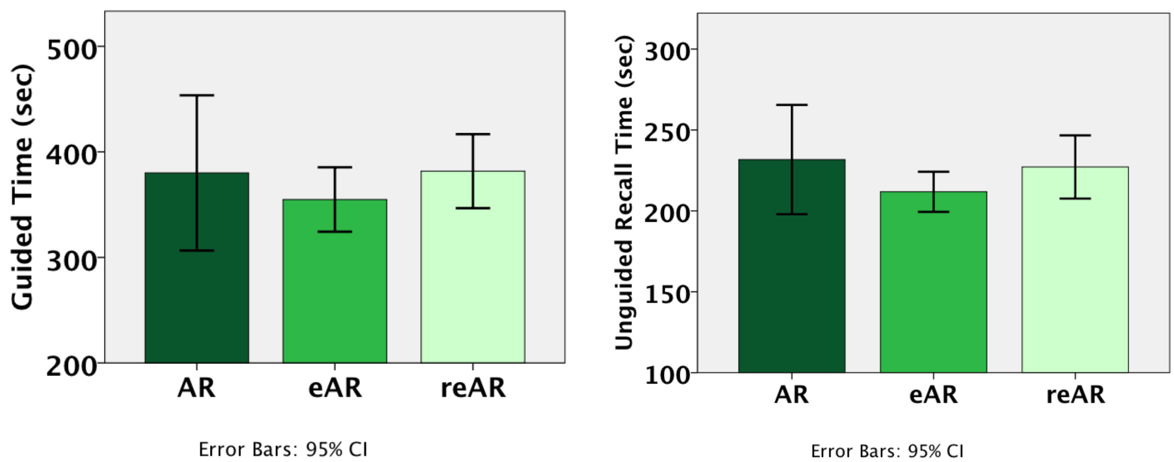


Figure 8.6: Performance measurements from guided traversal (left) and unguided recall traversal (right).

with the expected values although the differences were not significant between the interfaces, $F(2, 73) = 2.151, p = .125$. This can be seen in Figure 8.6 (left).

Unguided Recall Traversal

For the recall traversal, the results also failed to yield statistically significant timing measures ($F(2, 73) = .88, p = .42$) although the general expectation that the mean recall time for AR should be longer than for both eAR and reAR was evidenced. Specifically, AR users took the longest mean time to re-traverse the path ($M = 232.86s, SD = 88.76s$). Users of the reAR interface took less time on average ($M = 219.71s, SD = 35.65s$) while users of the eAR interface took the least time on average ($M = 215.72s, SD = 34.46s$). This is shown in Figure 8.6 (right).

8.4.3 Accuracy Results

As done previously, the accuracy results reported are based upon the number of incorrect turns made by participant.

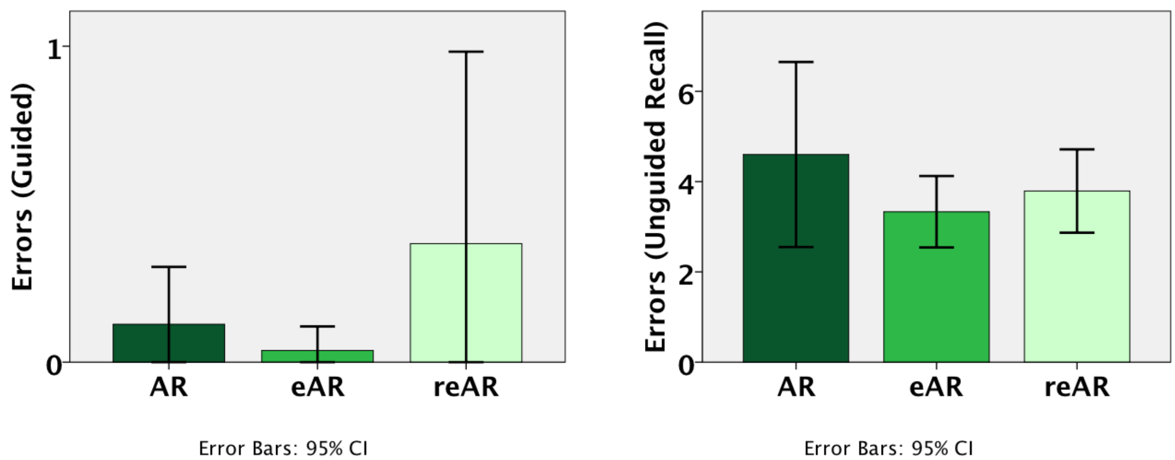


Figure 8.7: Accuracy results from guided traversal (left) and unguided recall traversal (right).

Guided Traversal

Errors made in the guided traversals were relatively low, as expected. AR users had a low mean ($M = .12, SD = .44$) and eAR users had no errors ($M = .04, SD = .19$). Users of reAR exhibited a wider range of errors ($M = .38, SD = 1.44$). This is shown in Figure 8.7 (left).

Unguided Traversal

Errors made in the unguided traversals yielded no significant differences between the interfaces. AR users had the highest mean ($M = 4.60, SD = 4.97$) and eAR users had the lowest ($M = 3.33, SD = 2.00$), while reAR users were between the two ($M = 3.79, SD = 2.19$). This is shown in Figure 8.7 (right).

8.4.4 Tool Usage Results

As before, we report on the number of times users requested the navigation tools and the total time spend using the navigation tools. Table 8.2 shows the observed usage behavior for the number of times the navigation tool was requested and the total amount of time the navigation tool was used.

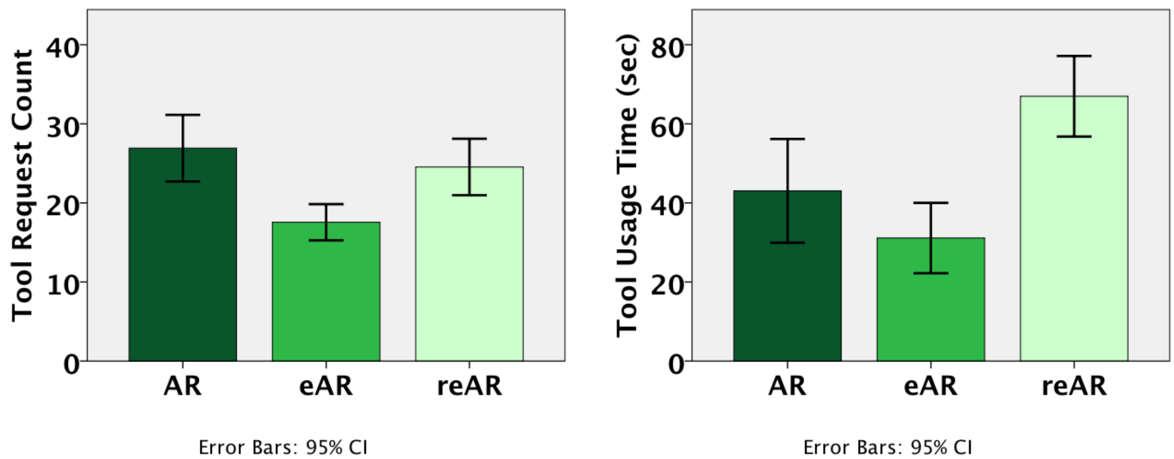


Figure 8.8: Navigation tool usage: tool request (left) and total usage time (right).

	Tool Request		Tool Usage Time	
	Mean	**Std dev**	**Mean**	**Std dev**
AR	26.92	10.20	43.04s	31.79s
eAR	17.56	5.79	31.11s	27.50s
reAR	24.54	8.45	66.96s	24.15s

Table 8.2: Request and usage time of the navigation tool

	AR M, SD	**eAR M, SD**	**reAR M, SD**	**F(2,73)**	**p**
map skill	2.12, 1.39	1.67,1.44	1.83, 1.049	.79	.46
tech skill	2.68, 1.75	2.33,1.64	2.29, 1.43	.44	.65
SBSoD	4.58, .87	4.96, 1.1	5.15, .89	2.24	.11
SUS	31.52, 8.78	33.37, 13.39	29.04, 7.27	.91	.41
TLX	7.52, 2.12	7.28, 2.25	8.091, 2.20	1.13	3.3
Mental	10.48, 4.28	9.48, 4.80	10.82, 4.21	.59	.56
Physical	2.80, 2.58	4.64, 5.14	10.82, 4.21	1.41	.25
Temporal	6.24, 4.28	5.04, 4.15	7.23, 5.00	1.41	.25
Perfomance	10.96, 4.80	11.68, 5.94	11.18, 4.72	.13	.88
Effort	9.72, 4.53	8.52, 4.55	10.95, 3.70	1.88	1.61
Frustration	7.56, 2.12	7.28, 2.25	8.09, 2.20	.23	.79

Table 8.3: Subjective data: Mean, standard deviation, One-way ANOVA F and p values

Using a one-way ANOVA, we found significant differences between interface conditions for tool request count ($F(2,73) = 9.027, p < .001$) and total tool usage time ($F(2,73) = 12.02, p < .001$). Using a post hoc Bonferroni analysis, we found that that eAR users invoked navigation guidance significantly less than both AR users ($p < .001$) and reAR users ($p < .05$). We also found that reAR users took a significantly longer time using the guidance tool than both AR users ($p < .01$) and eAR users ($p < .001$). Figure 8.8 illustrates the differences observed.

8.4.5 Subjective Results

None of the subjective data collected yielded any significant differences after applying a one-way ANOVA to compare the interface conditions. The results are summarized in Table 8.3.

8.4.6 User Feedback

Many user comments were directed at the simulation interface regarding speed (too slow), the keyboard interface (didn't have enough controls, e.g., sideways movement), or graphics (lacking details). However, many participants also made observations more directly related to the heart of the study. For example, regarding the lack of a continuous display of the directional path, one eAR participant expressed frustration at "not being able to see the green line at all times, so I know ahead of time where I am going." However, another eAR user noted the cost of such continuous help: "navigation tool (the green arrows on the ground) made me go on autopilot and distracted me from looking around at landmarks (buildings/hills) and street signs."

Reaction to the quizzes was mixed. One eAR user appreciated that "the building distractor tasks actually helped me remember the path—among the many similar buildings I think at least once I made a decision based on the shape of the windows of the building at the intersection I had to turn." A participant who had the reAR condition related it to actual practice: "Now that I think about it, when I am in a city I am not familiar with I take mental pictures like those we were quizzed on to help me remember where things are."

However, one eAR user thought the system was "not particular *[sic]* useful for me in recalling where I had walked previously" while another eAR user felt frustrated at "needing to stop to match a building to a thumbnail...Also, I prefer knowing my turns ahead of time without having to press a button to ask."

Some participants saw the need to regard such a system as a potential investment in effort and one eAR user remarked that "if I knew that identifying landmarks would actually help me, I would use it, otherwise it seems too cumbersome." Another noted that reAR "actually helped me remember the path. I prefer landmarks for navigation over e.g. street names, so having navigation software that teaches me landmarks along a trip would be very helpful."

Perhaps viewing the simulation from a gaming perspective, one eAR user left the comment that "It was fun, mildly stressful, and as a result engaging."

8.5 Discussion

This study set out to better understand how pedestrian navigation tools can balance navigational efficiency with spatial knowledge acquisition by way of increasing user effort. By integrating the spatial knowledge acquisition features into the navigation process, it was hoped that the interaction would be acceptable perhaps even appealing, from a usability perspective. It was nonetheless expected that, by adding in an effortful unit of operation (from AR to eAR), users may invoke the tool less since the process is made more tedious. While this was indeed observed, it did not seem to apply to reAR, which was unexpected.

It could be possible that beginning every reAR guidance request with a quiz in the Effort Zone resulted in a substantial distraction from the directional cues provided. Whereas eAR only distracted the user once, reAR's repeated attempts to increase user awareness may have been excessive. This brings up a fairly interesting possibility: too much of a spatial knowledge tool may actually detract from the primary navigation purpose of the overall tool. Just as navigation tools may diminish the formation of cognitive maps, the repeated quizzes designed to improve spatial knowledge may do so at the expense of the primary task of navigation. It is possible that this would result in a greater need for navigational guidance which, in turn, may lead to a feeling of greater perceived demands and stress, as described by the inverted-U performance curve of Figure 8.9 that shows how optimal performance may lie between the extremes of perceived stress [102]. As such, care needs to be taken when introducing spatial awareness features lest they interfere with the primary navigation information.

The lack of statistical significance in the performance and accuracy measurements prevents us from measuring the degree of mental map formation based upon the recall tasks. While the small effect size is expected for the on-line study, in the real world—or more complex virtual environment—it is likely that the effects of the interface conditions on the recall task would be larger so that the improvements in spatial knowledge acquisition would be more apparent.

Based on the user comments, it seems reasonable to expect that an increase in user interaction would be acceptable by some users if the rationale and potential benefits of

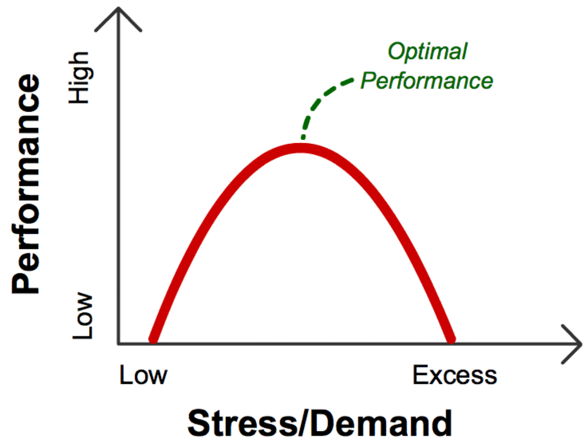


Figure 8.9: The performance-stress curve describes a point of optimal performance where the perceived stress/arousal/demand is neither too small nor too great.

the interaction is made clear. Furthermore, there appears to be a potential to gamify the interaction so as to improve user engagement in an appealing fashion. For example, introducing landmark-based recognition exercises at strategic locations—and perhaps with an opt-out feature—could actually be welcomed by users who are made aware of the purpose of the additional features and can benefit from the results.

8.6 Conclusion

Based upon existing work indicating that increasing the effort on the part of the user will potentially result in greater acquisition of spatial knowledge, we designed a navigation tool that would produce a quiz-like interaction from the user at a certain point from an upcoming decision point. From a user interaction perspective, we took care to ensure that the additional interaction would not be so tedious or irrelevant as to cause a user to become annoyed by the system. A study was completed that compared a basic AR navigation tool. with interfaces that used the same tool but added spatial awareness-related quizzes when a user approached an intersection.

Our results hinted at a trend indicating that such an interface would, in fact produce the desired result in terms of better route knowledge, as measured by the performance time and accuracy achieved in traversing the same path entirely from memory. Significant differences in tool usage behavior indicated that there is potentially an ideal degree to which the introduction of spatial knowledge cues can result in more efficient tool usage. Furthermore, user feedback indicated that such features may be welcomed if their purpose is clear. For designers, this means there is a need to be clear about the feature benefits and to exercise some finesse in creating features meant to improve spatial knowledge.

9

Discussion

The previous five chapters detailed the studies we conducted in pursuit of the research question and goals. Each chapter offered a section that discussed the ramifications of the study. In this chapter, we take a step back and offer thoughts relating to the work from a broader perspective, casting a wide net over the studies to discuss issues that have broad implications in the overall thesis. We look at the lessons learned, discuss the limitations of our studies, and offer some guidelines based upon our findings.

9.1 Lessons Learned

In this section we return back to the original research goals from Chapter 3 and discuss the overall lessons learned from the studies related to the goals. In this way we provide a high level discussion.

Research Goal #1: Establish a baseline performance measurement of map-based and AR-based pedestrian navigation tools for primed searches.

This research goal was addressed by the Nav1, Nav3 and Nav4 studies from Chapters 4, 6, and 7, respective, as well as the HMD study described from Appendix H. From these studies we learned that an AR-based pedestrian navigation tool, while theoretically easier than maps for use in outdoor guidance, did not perform as expected (Nav1). Having just a target direction shown was good for general orientation but, when obstructions needed to be negotiated, the limited overview of the area became a factor. Tracking errors affected usage and often required a substantial amount of waiting for the visual cue to stabilize into a steady directional indicator. In order for AR to be a practical tool, such problems will need to be resolved.

However, by using a simulated environment to remove these AR tracking errors, and using route based AR cues, we were able to see how an AR-based navigation tool can yield better performance results than maps (Nav3, Nav4, and HMD studies). In this case users were indeed able to navigate through a virtual city far faster with an AR tool than with a map tool. As discussed in Section 2.3.2, AR resolves many of the difficulties associated with maps and, as such, the faster performance using AR tools aligns with expectations.

Research Goal #2: Compare route knowledge acquisition between users of map-based and AR-based pedestrian navigation tools.

This research goal was addressed by the Nav3 and Nav4 experiments from Chapters 6 and 7, respectively, as well as the HMD study described in Appendix H. From these studies we learned that when asked to recall the path, AR users made far more errors than map users and the recall of the path took substantially longer for AR users than for map users. This aligned with our basic assumption. The presumed lower cognitive demands of AR translated into faster performance results, but poorer knowledge acquisition.

In a dual task setting, map users exhibited significant drops in both guided and unguided recall performance times when compared to single task map users. However, the time for recalling the route is still significantly better than the guided route although significantly worse than for single task map users. This suggests that map users are acquiring spatial knowledge just by virtual of using the map although the secondary task does penalize the results so that they do not perform as well as single task map users. AR users, on the other hand, seem to be relatively insulated from the effects of a secondary task, exhibiting no significant differences in both guided and unguided recall tasks between single task users and dual task users. This suggests that AR users may have the capacity to take on secondary tasks that could potentially help them improve spatial knowledge without having their performance penalized.

Research Goal #3: Collect data in order to compare user preferences with actual usage behavior when a choice of pedestrian navigation tools is available.

This research goal was addressed by the Nav2 experiment. We found that, when provided with a number of navigation interface options, users would, over time, settle in on a subset of tools they preferred. We saw that users overwhelmingly preferred the Forward-up map interface and that it may offer dual appeal to both survey-oriented users as well as directionally-oriented users. We also suspected that the familiarity with maps and the resolution of map reading challenges made Forward-up maps appealing.

Although some increase in AR usage was detected in a phase-based analysis, the dominance of Forward-up maps made the relatively small changes less meaningful. Taking Forward-up maps out of consideration, we did see that there was an increase in AR usage in the latter phases of navigation possibly indicating a desire to address one of the challenges of map reading, which is the association of symbols on the map with landmarks in the actual environment. However, we found that overall, users did not rate AR very highly, which may be a perception that AR is difficult to use given the frustrations of having to deal with the poor tracking.

Research Goal #4: Analyze usage data in order to create a classification of pedestrian navigation tool user types.

This research goal was also addressed by the Nav2 experiment. We found that the different usage patterns provided us with the possibility of creating a classification for different preferences that could help with tool design. The alignment of our results with other studies using different methodologies suggests that such a categorization may be consistent and, as such, may be valuable for defining design guidelines and constraints for pedestrian navigation tools that would cater to innate usage preferences.

Research Goal #5: Find an objective measure of the relative demands imposed by map-based and AR-based navigation tools.

This was addressed by the Nav4 user study where subjects had a secondary task to perform while navigation. This provided us with insights into the relative amount of cognitive resources needed to devote to the primary task and how the competition for resources may impede on the performance of both tasks. We saw that map users performance degraded substantially while AR users did not show any significant changes in time-on-task performance. This indicated that map users had to sacrifice considerable cognitive resources in order to perform a secondary task and so, in the process, the primary task suffered.

AR users, however, seemed to be able to handle the secondary task relatively easily and did not produce a significant drop in task performance. Specifically, AR users were also able to recall more words, showing that they were able to handle the secondary task better and still perform well in the primary task while map users did not do as well in the secondary task word recall and also performed significantly worse in the primary task. This approach provided us with a valuable way to objectively measure cognitive effort which is generally based on more subjective measures, such as self-assessed surveys. Our results implied that we may be able to created spatial knowledge building interfaces into navigation tools based upon AR and expect users to benefit from the tools without degrading their navigation performance significantly.

Research Goal #6: Attempt to use AR to define landmark-based cues in a request-based pedestrian navigation tool that seeks to improve the acquisition of route knowledge without sacrificing guided traversal performance.

This was addressed by the Nav5 experiment which tested on possible use of AR cues for highlighting landmarks. This yielded results that suggested such features may have an optimal range within which they would help in the acquisition of spatial knowledge. By including spatial knowledge building features in a manner that is integrated with the navigation interface, the navigation tool may address usability issues so as to appeal to users but, at the same time, provide the added benefit of helping to strengthen spatial knowledge.

9.2 Limitations

In this section, we offer some thoughts about the limitations of the user studies conducted. Our thesis is based upon the premise that AR-based navigation tools require a lot less effort and, as a result, the formation of route knowledge suffers. The measure of effort is usually a subjective one, which we addressed with the dual-task study of Chapter 7. Our choice to base our measurements on performance is supported by prior work evaluating mobile pedestrian navigation tools by time-on-task performance although it should be noted that performance is also a measure of proficiency, which may be more indicative of a user's experience rather than the nature of the technology in question. The self-assessment questions administered in our pre-test questionnaires that judged participant proficiency with map and technology tools were meant to account for such individual differences. While many measures of spatial knowledge are based upon distance and direction estimates as well as sketch maps, our focus on route knowledge through re-traversal reflects its procedurally-based nature and, as such, may be more relevant than survey-based tests, which may test other aspects of spatial memory. In this way, a virtual setting is also more practical given the lower demands when compared to real world re-traversals, which may be impractical given the physical exhaustion that may arise from multiple traversals of urban paths.

The fundamental transition from the real world to a virtual environment was neither foreseen nor planned when the initial research was defined. As noted in Chapter 6, our motivation for the shift was based on the need for accurate GPS data. While the ultimate test of a pedestrian navigation tool would be one where the participants are using them in actual real world settings, our work is based upon a large corpus of work undertaken in a virtual setting in the interest of gaining insights into real world behavior. Although consistency is still a concern and transfer (of spatial knowledge from the virtual to the real world) is not assumed, it can be argued that the change allowed us to focus more on the basic science underlying the relationship between navigation performance and spatial knowledge acquisition rather than on the applied engineering details of the interfaces.

That said, the move to a virtual environment is not free of engineering issues. Because the use of a desktop system for virtual simulations may lack immersion that may affect experiments seeking to study spatial knowledge acquisition, we conducted an exploratory study comparing desktop and head-mounted display (HMD) systems for establishing our premise. Like our desktop study, AR-based tools performed faster than map-based tools in Guided navigation, as expected. But unlike the desktop study, the Unguided Recall traversal data for the HMD system was inconclusive. This may have been due to the poor resolution of the HMD. However, a full pursuit of this would have re-directed our research into the notion of virtual environment presence, which is substantially distinct from our main focus of relating pedestrian navigation efficiency with spatial knowledge acquisition. The results of that study is reported in the Appendix H for the reader's reference.

Finally, a thesis relating to human factors with AR pedestrian navigation tools will need to address the very real concerns of the social cost in using mobile AR tools: people holding up their devices to properly view AR may be seen as taking photographs or videos and, as such, their actions may be mis-interpreted as invasive or otherwise intrusive. While the recent ejection from a restaurant of a patron wearing Google Glass AR glasses [1] may be an artifact of a transitional phase before such technologies are accepted, the ability to conduct such studies in the real world is confounded by such factors and, as such, may further favor studies done in a more controlled environment.

9.3 Guidelines

Our studies provided us with valuable insights that could help inform future studies. Here, we offer some guidelines that would be helpful for evaluating and designing mobile pedestrian navigation tools.

To counteract the effects of poor tracking, avoid guidance that is highly dependent on precise positioning. Distant or large scale destinations may work better due to the lack

[1] http://www.forbes.com/sites/matthickey/2013/11/26/seattle-diner-booting-customers-for-wearing-google-glass/

of need for precise placement. For closer locations or small objects, it would be useful to provide an indicator of GPS accuracy so that users can understand the underlying cause of the potentially frustrating interaction process where the AR cue needs to be stabilized.

Tools that offer multiple interfaces may be able to deal with a broader set of navigational conditions. By analyzing usage behavior, tools can be designed to properly target different types of users. Such information can be collected by offering users a training phase where they are given an opportunity to become familiarized with the features and functionalities of the interface (possibly with a time-out mechanism to force consideration of the choices). By combining the data gained from the training process with some questions regarding their background, navigation tools can be tailored to work comfortably with a user based upon their personal preferences.

In lieu of accurate GPS data in the real world, simulated environments for testing navigational tools may allow for users to be tested for route memory by repeating the traversal without incurring the physical exhaustion that real world navigation tests would. Because traditional mental maps measurements may not work as well in a simulated environment, the use of re-traversals may offer one measure that is not easily repeated in the real world. The degree to which users are familiar with gaming interfaces may impact performance and so a thorough and engaging training session is essential.

In a VE, the use of a dual task to measure relative cognitive effort can be used in a variety of ways to test cognitive demands, which relates to the ease-of-use of navigation tools. Dual tasks could be introduced to provide a measure of the effort required by the particular user of a tool. The degree to which users can fulfill a primary task (e.g., navigation) without incurring substantial degradation in performance while addressing a secondary task, could be used as an indicator of the potential of the interface to increase effort on the part of the user in order to improve spatial knowledge acquisition.

Introducing features to help build spatial awareness into an AR-based tool may be most effective if the feature is carefully calibrated to provide some benefit without becoming overbearing.

In Table 9.1, we summarize the lessons learned and the guidelines we offer.

Study	Lessons Learned	Guidelines
Nav1	Real world AR performance not faster than maps Directional AR may lead to dead-ends Neither AR nor map favored by users when combined Tracking errors may make use of AR difficult	Avoid precise AR (until better tracking) Show GPS accuracy
Nav2	Learning effects exists when given multiple interfaces User behavior differences can be distinctly classified Forward-up maps are heavily favored Phase-based interface preference exists but small AR is not a preferred interface	Offer AR option when near destination Tailor UI to user type
Nav3	AR is faster than maps with perfect tracking in VE AR path recall is slower than map in VE	Provide VE training for interface Use re-traversal for testing recall
Nav4	Dual task degraded map performance but not AR Dual task did not affect accuracy Map faster recall than AR in dual task mode AR users were better at secondary task	Use dualtask to measure relative load
Nav5	SK building features may have optimal zone	Calibrate spatial knowledge building UI

Table 9.1: The studies and corresponding takeaways.

10
Conclusion

This dissertation is premised upon an interest in how advances in AR technology can have an impact upon the way pedestrians find their way around unfamiliar environments. Our interest was not limited to the expected positive benefits of increased efficiency; we also wanted to give fair and balanced consideration to the possible negative consequences. Specifically, we wanted to address the concerns related to how AR may improve the ease-of-use and performance of pedestrian navigation tools but at a cost: our ability to form mental maps of areas we had previously navigated through with guidance may diminish, making us potentially more dependent upon a technology that may fail at any time. Our thesis has, at its core, a desire to understand the relationship between the gains in navigational efficiency and ease against the loss of route knowledge acquired. In this chapter, we provide a brief summary of the work and findings of this dissertation, discuss some lessons learned, and propose directions for future work.

10.1 Summary of Thesis Work

We first re-state the research question: *How does AR-based navigation compare to map-based navigation in terms of performance, mental map formation and cognitive effort required, and can AR tools be developed to improve recall of navigated paths?*

In order to explore this question, our first task was to establish our assumption that AR would, in fact, provide more efficient navigation when compared to maps, in an outdoor environment (Nav1 from Chapter 4). To our surprise, our study did not yield data to support this assumption: no significant differences were detected between map and AR interfaces for time-on-task performance. In addition to not performing as well as we had expected, when given a choice between map and AR interfaces, we found no conclusive evidence that AR would be preferred by users.

Our second study explored this further and sought to measure user perception with respect to AR navigation tools and how their expressed preferences align with actual usage (Nav2 from Chapter 5). We found that users did not favor AR and, in fact, considered it one of the least appealing tools to use for navigation. We created a classification of user types that helped us to understand potential underlying preferences based upon personality types that would have practical applications in interface design for pedestrian navigation tools. Based upon the results of our studies and the state of the art, we identified inaccurate GPS data as a possible cause for the unexpected poor performance and negative perception of AR tools.

To verify this possibility, we built a testbed that offered simulated perfect AR tracking, dubbed the SPART (*Simulated Perfect Augmented Reality Tracking*) system. Our preliminary study in SPART allowed us to verify our underlying assumption that AR-based pedestrian navigation technology could yield better time-on-task performance than map-based pedestrian navigation technology (Chapter 6). Additionally, we were able to collect data that supported our hypothesis that the increased ease with which an AR-based navigation tool could guide a user through an urban environment penalizes the formation of cognitive maps in terms of performance with respect to route recall.

We then used a modified SPART system to include a secondary task during navigation so that we might obtain a more direct and objective measure of the ease-of-use of AR-based navigation tools (Chapter 7). The quantitative results gave us insights into the cognitive capacities of map and AR users to handle secondary tasks. Using evidence from the literature that landmark cues are fundamental to navigation, we were able to conceive of a tool that attempts to exploit the time savings gained from AR to provide users with landmark cues to improve route memory (Chapter 8). Our results were encouraging in the positive trends exhibited although more data is needed to achieve significance.

10.2 Contributions

The studies completed in this thesis contribute to an increase in our understanding of mobile pedestrian navigation tools as well as the specific impact of AR pedestrian navigation tools on the formation of spatial knowledge. In particular, our contributions include:

- One of the first comparative studies of outdoor targeted search with mobile pedestrian navigation tools based on maps, AR, and the combination of the two. Our results indicated that the assumption that AR would offer more efficient navigation performance may not be valid. We also found that offering multiple interfaces for users may be a worthwhile direction for pedestrian navigation tools.

- One of the first studies of user preferences given a choice of mobile pedestrian navigation tools and an imposed mechanism to force periodic consideration of the options. We found that user assessments of tools based on exclusive usage may align well with tools used in concert. We also found that performance may not be an ideal indicator of actual usage choice.

- A classification of pedestrian navigation tool users based upon usage behavior. Based on usage behavior, we identified four user categories that could provide guidance in the designing of pedestrian navigation tools. Our results aligned well with previous findings and extended the methodologies that could be used for classifying users.

- The creation of a testbed for simulating perfect location-based tracking for testing AR guidance technology. Our SPART system allowed for extensions to test interfaces with additional features and distractors in a controlled setting. Results from SPART allowed us to see how AR pedestrian navigation tools may behave in the near future.

- The application of a dual-task methodology to assess the cognitive load demands of navigation tools. Usability measures for pedestrian navigation tools are generally based on subjective user assessment surveys but the dual task approach provides an objective measure. Our study provided insights into how much cognitive resources may be required by AR and map based pedestrian navigation tools.

- The design of a simulated pedestrian navigation tool that seeks to use landmark-based cues to strengthen the acquisition of route knowledge. We implemented an interface that requires a user to become more engaged with the surrounding environment but without sacrificing navigation efficiency. Our exploratory study indicated that there is potentially an ideal amount of spatial knowledge building features that can be included into a navigation system.

Returning to the hypothesis organization introduced in Chapter 3, Table 3.1, Table 10.1 summarizes these contributions as they relate to our original research goals. As can be seen, five of the six hypotheses were supported by experimental data. The user study conducted for hypothesis six produced inconclusive results, but this is an area for continued future study.

10.3 Future Directions

Our research has made a number of important contributions to further understanding of how mobile AR can impact pedestrian navigation. However, it has also opened up a number of areas for further work, including

- Outdoor SPART - Improve AR tracking by supplementing GPS data with additional tracking methods (marker-based tracking, hybrid tracking, or other technologies) to simulate perfect tracking in an outdoor urban environment in order to establish performance measurements for AR vs maps, as from Chapter 6.

- Understand the dual nature of Forward-up maps - The potential dual role of forward-up maps (see Chapter 5) is intriguing and may be exploited as a means to balance wayfinding and mental map formation. By conducting studies similar to the dual-task studies from Chapter 7, it may be possible to better understand if users who seem to use forward-up maps as directional tools indeed have poorer mental maps and, if so, if the cartographic nature of forward-up maps would help build better survey knowledge.

- Explore the differences between North-up maps with and without YAH markers in terms of cognitive effort required and consequential route recall. By removing the challenge of self-location, which is necessary for maps but not for AR, the MY condition from Chapter 6 would have eased some of the challenges in map reading. The decrease in spatial knowledge acquired would offer additional data for assessing the relationship between navigational tool ease-of-use and the acquisition of spatial knowledge.

- Quantify navigation ease-of-use vs spatial knowledge acquisition relationship - While the work in this dissertation was largely based around AR navigation tools, the more general relationship between navigation technology ease-of-use and cognitive map formation is likely to follow a similar relationship. It may be possible to aggregate the possibilities into a continuum if not a quantifiable relationship based upon the methodologies explored in this thesis.

- In a dual-task environment, monitor when users switch to the secondary task. It is not clear how well and how often users are able to divert from consulting the navigation tool when a secondary task competes for attention. If, however, users only pay attention to the secondary task when they are not consulting the navigation tool (walking or not moving) then the impact of the secondary task may be very different.

- Engage users of pedestrian navigation interfaces - Adding interaction to engage users may help improve spatial awareness but it may be difficult to motivate users to commit increased effort. Techniques of gamification may motivate users to interact more with a tool that is more enjoyable or rewarding while being designed to convert the increased interaction into improved spatial knowledge.

- Conduct enhanced AR pedestrian navigation tool in an outdoor environment. Although our final study, Nav5, yielded some significant findings with respect to tool usage, performance results were inconclusive. Given the limitations of a simulated environment, the effect size was expected to be small (approximately .18 - see Section 8.3). We would expect a larger effect size in a real world environment.

- Conduct studies that target potential gender differences so that tools can be designed to cater to innate skills and abilities that have been found to be gender-based.

- Explore more specific mental map tools that target route knowledge, particularly in virtual simulated environments. While virtual simulations offer numerous advantages over real world navigation studies, it largely relies upon measurements created long before digital navigation tools were available (e.g. absolute distance estimates, sketch maps). Such mental map measurements may be more suitable for configural tests (e.g. survey knowledge) rather than procedural tests (e.g. route knowledge). Re-traversal is arguably the best approach for testing route knowledge but, practically, it is difficult to do in the real world and so tests are generally based upon picture recognition and relative estimates in direction and distance. In a virtual setting, there is a potential of having a user re-traverse the route, possibly at a much higher speed. In this way, the entire environment is re-produced and, as such, measurements based within such an environment may be ideally suited to understanding what a person has been able to acquire in terms of spatial knowledge.

- Include the eAR condition of Nav5 into the dual task study of Nav4 and have all participants perform both Single and Dual task traversals so as to collect data that can indicate if the performance to route knowledge acquisition relationship is generally linear or non-linear. Further adding the Forward-up map (Nav2) and MY (Nav3) conditions would allow us to attempt to search for a broader understanding of the relationship between navigation tool efficiency and cognitive map formation.

By building a firmer understanding of the relationship between the usage of pedestrian navigation tools and the formation of cognitive maps, we may strike an ideal balance where users can find their way around environments with desired efficiency while also acquiring a healthy amount of spatial knowledge. Being cognizant of the need to "practice our memory" may speak to something more than a desire to avoid an over-dependency on technology and the consequential helplessness that may leave us literally—in the case of pedestrian navigation tools—in a bad position. As technology continues to progress at an amazing rate and becomes increasingly integrated into all facets of our lives—it may also speak to a desire to retain some small part of our human-animal roots, if not humanity. It is hoped that the work of this dissertation will contribute, in its small and focused corner of the world, to reaching this ideal balance.

Goal	**Hyp.**	**Study**	**?**	**Contributions**
RG1	**H1**	Nav1	N	Compared map and AR navigation performance
		Nav3	Y	Created testbed for simulating perfect AR tracking
		Nav4	Y	Compared performance with dual tasks for maps and AR
		HMD	Y	Compared immersion level for map and AR navigation
RG2	**H2**	Nav3	Y	Assessed route memory with perfect AR tracking
		Nav4	Y	Compared SKA with dual tasks for maps and AR
		HMD	N	Found possible drawback for HMD immersive experience
RG3	**H3**	Nav2	Y	Found phase-dependency in navigation tool preference
RG4	**H4**	Nav2	Y	Created classification of pedestrian navigation tool users
RG5	**H5**	Nav4	Y	Observed better handling of dual tasks by AR users
RG6	**H6**	Nav5	I	Detected optimal zone for presenting SK features

Table 10.1: Research goals and contributions (4^{th} column indicates support of hypothesis)

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Appendices

A
Nav1 Questionnaire

General Information

1. Gender: M / F Age (years): _______

2. Eyesight problems / defective vision: yes / no

   If yes, please describe: ____

   Is it corrected (glasses, etc.)? yes / no

3. What kind of mobile phone do you generally use?

   ☐ Smart phone (iPhone, Nokia N series, Windows mobile, Android phone,…)

   ☐ regular mobile phone

Daily mobile phone usage	never	Less than 30 min.	30 min. – 1 hr	1-2 hrs	3-5hrs	More than 5 hrs
making phone calls	☐	☐	☐	☐	☐	☐
TXT, SMS, MMS	☐	☐	☐	☐	☐	☐
Web browsing, email	☐	☐	☐	☐	☐	☐
Organizer / Calendar	☐	☐	☐	☐	☐	☐
Multimedia (music, video, photos, etc.)	☐	☐	☐	☐	☐	☐
Navigation (GPS)	☐	☐	☐	☐	☐	☐

	never	Once per month	Once per week	Most days	Daily
How often do you use **GPS** navigation (GPS unit, phone in car navigation system)	☐	☐	☐	☐	☐
How often do you use **paper maps**	☐	☐	☐	☐	☐
How often do you use electronic maps (e.g. **Google maps**)	☐	☐	☐	☐	☐

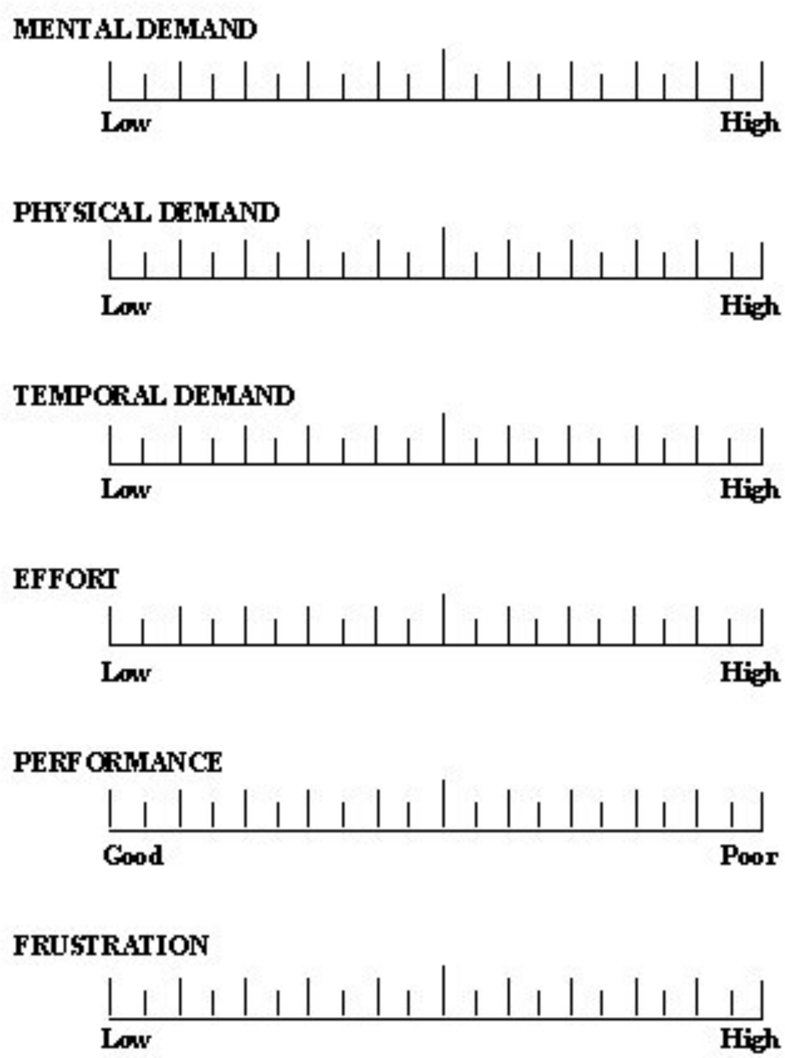
	(completely disagree) ---	--	-		+	++	(completely agree) +++
I am good at using maps	☐	☐	☐	☐	☐	☐	☐

Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

Map

	(completely disagree) ---	--	-		+	++	(completely agree) +++
It was **easy to use** the interface	☐	☐	☐	☐	☐	☐	☐
The interface was **useful** to complete the task	☐	☐	☐	☐	☐	☐	☐
The interface was **intuitive**?	☐	☐	☐	☐	☐	☐	☐
It was **easy to identify** the Points of Interest on the interface	☐	☐	☐	☐	☐	☐	☐
I was **aware** of where I am going all the time	☐	☐	☐	☐	☐	☐	☐
I **felt lost** during this experiment	☐	☐	☐	☐	☐	☐	☐
I would actually want to **use** this tool in **everyday life**	☐	☐	☐	☐	☐	☐	☐
I **performed well** with this interface	☐	☐	☐	☐	☐	☐	☐

Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR



Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

Augmented Reality

	(completely disagree) ---	--	-		+	++	(completely agree) +++
It was **easy to use** the interface	☐	☐	☐	☐	☐	☐	☐
The interface was **useful** to complete the task	☐	☐	☐	☐	☐	☐	☐
The interface was **intuitive**?	☐	☐	☐	☐	☐	☐	☐
It was **easy to identify** the Points of Interest on the interface	☐	☐	☐	☐	☐	☐	☐
I was **aware** of where I am going all the time	☐	☐	☐	☐	☐	☐	☐
I **felt lost** during this experiment	☐	☐	☐	☐	☐	☐	☐
I would actually want to **use** this tool in **everyday life**	☐	☐	☐	☐	☐	☐	☐
I **performed well** with this interface	☐	☐	☐	☐	☐	☐	☐

Which view was **more helpful**?

The small radar view The AR view

☐	☐	☐	☐	☐	☐	☐

Which view one did you use **more often**?

The small radar view The AR view

☐	☐	☐	☐	☐	☐	☐

Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

EFFORT

Low High

PERFORMANCE

Good Poor

FRUSTRATION

Low High

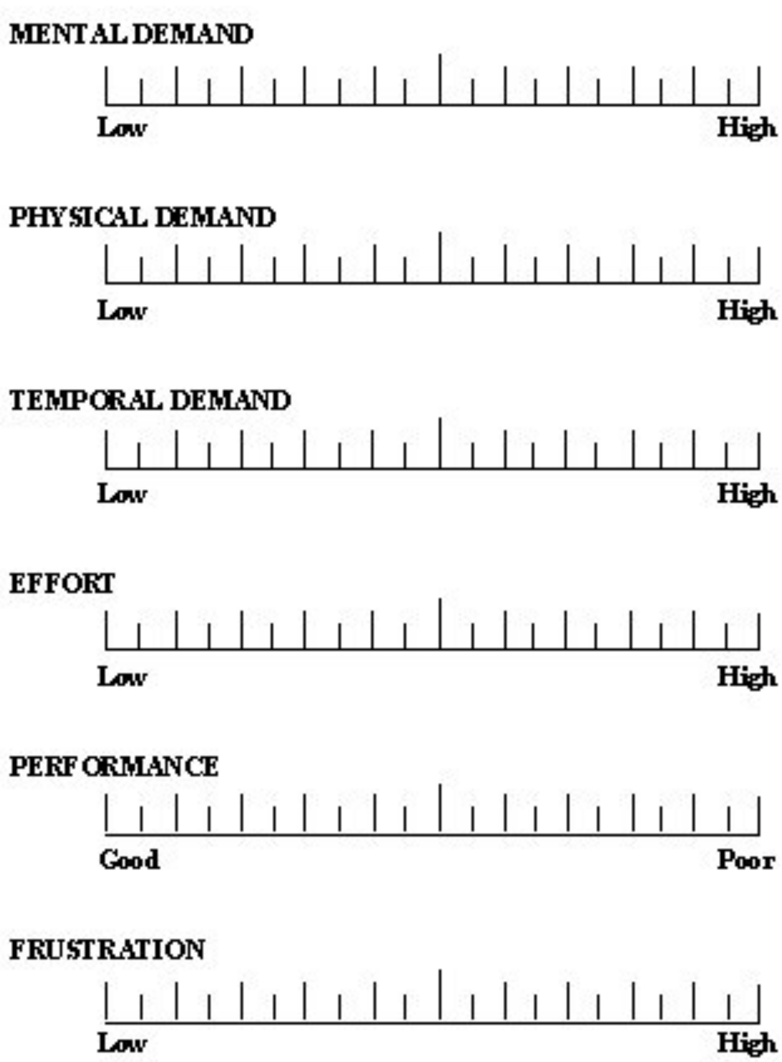
Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

Augmented Reality & Map

	(completely disagree) ---	--	-		+	++	(completely agree) +++
It was **easy to use** the interface	☐	☐	☐	☐	☐	☐	☐
The interface was **useful** to complete the task	☐	☐	☐	☐	☐	☐	☐
The interface was **intuitive**?	☐	☐	☐	☐	☐	☐	☐
It was **easy to identify** the Points of Interest on the interface	☐	☐	☐	☐	☐	☐	☐
I was **aware** of where I am going all the time	☐	☐	☐	☐	☐	☐	☐
I **felt lost** during this experiment	☐	☐	☐	☐	☐	☐	☐
I would actually want to **use** this tool in **everyday life**	☐	☐	☐	☐	☐	☐	☐
I **performed well** with this interface	☐	☐	☐	☐	☐	☐	☐

I spent ____% of my time using the map view.

Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR



Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

		Preferred interface	Which let you **perform** the **best**?	Which would you use to get to a Point of interest the **fastest**	Which would you use to get to a Point of interest with the **least errors**
Please **rank** the 3 interfaces from **1 to 3** (**1 = best**). Give **one (different) number for each**.	Map				
	Augmented Reality				
	Augmented Reality & Map				

Please give some more detailed comments:

Participant code	*Date*	M - AR - MAR
		AR – MAR - M
		MAR – M - AR

B

Nav2 Questionnaire

NE2B **Participant Questionnaire** **ID: ______**

1. Gender: M / F
2. Age: ______ yrs
3. Eyesight problems / defective vision: Y / N (If Y, is it corrected - e.g. glasses? Y / N)
4. My work/study/background is in the field of: ________________________
5. What kind of mobile phone do you use? Standard mobile phone / Smart phone

I am familiar with the Punavuori area	|----------|----------|----------|----------|----------|----------|----------| Completely disagree Completely agree
I am good at using maps	|----------|----------|----------|----------|----------|----------|----------| Completely disagree Completely agree
I am comfortable with technology	|----------|----------|----------|----------|----------|----------|----------| Completely disagree Completely agree

Mobile Phone Time Spent

Activity	n/a	Never	< 30 min	< 1 hr	< 2hr	< 5 hr	> 5 hrs
Phone calls							
Web							
E-mail							
Organizer / Calendar							
GPS							

Mobile Phone Usage per Day

Activity	n/a	Never	~5	~10	~50	~100	> 100
Camera							
Text/MMS							
Map							

Non-phone Navigation

	Never	Once per month	Once per week	Most days	Daily
Paper maps					
Web-based maps					
In-car GPS Device					

Compass

Estimate the distance walked: _______ meters
Estimate the time spent: _____ minutes _____ seconds

The interface was **easy to use.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **useful** in completing the task.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **intuitive.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
It was **easy to interpret** where the Goal was.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Mental Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Physical Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Time Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Effort Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Frustration	|___|___|___|___|___|___|___|___|___|___| Low ... High

North Up Map

Estimate the distance walked: ______ meters
Estimate the time spent: _____ minutes _____ seconds

The interface was **easy to use.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
The interface was **useful** in completing the task.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
The interface was **intuitive.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
It was **easy to interpret** where the Goal was.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree

Mental Demand	|___|___|___|___|___|___|___|___|___|___| Low — High
Physical Demand	|___|___|___|___|___|___|___|___|___|___| Low — High
Time Demand	|___|___|___|___|___|___|___|___|___|___| Low — High
Effort Demand	|___|___|___|___|___|___|___|___|___|___| Low — High
Frustration	|___|___|___|___|___|___|___|___|___|___| Low — High

Forward Up Map

Estimate the distance walked: ______ meters
Estimate the time spent: _____ minutes _____ seconds

The interface was **easy to use.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **useful** in completing the task.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **intuitive.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
It was **easy to interpret** where the Goal was.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Mental Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Physical Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Time Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Effort Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Frustration	|___|___|___|___|___|___|___|___|___|___| Low ... High

Augmented Reality

Estimate the distance walked: ______ meters
Estimate the time spent: _____ minutes _____ seconds

The interface was **easy to use.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **useful** in completing the task.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **intuitive.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
It was **easy to interpret** where the Goal was.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Mental Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Physical Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Time Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Effort Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Frustration	|___|___|___|___|___|___|___|___|___|___| Low ... High

Radar

Estimate the distance walked: ______ meters
Estimate the time spent: _____ minutes _____ seconds

The interface was **easy to use.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **useful** in completing the task.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The interface was **intuitive.**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
It was **easy to interpret** where the Goal was.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Mental Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Physical Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Time Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Effort Demand	|___|___|___|___|___|___|___|___|___|___| Low ... High
Frustration	|___|___|___|___|___|___|___|___|___|___| Low ... High

Waypoint #1

Estimate the distance walked: ______ meters
Estimate the time spent: ____ minutes ____ seconds

Mark “1” for start of task, “2” for middle of task, “3” for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree

Waypoint #2

Estimate the distance walked: ______ meters
Estimate the time spent: ____ minutes ____ seconds

Mark “1” for start of task, “2” for middle of task, “3” for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Waypoint #3

Estimate the distance walked: _______ meters
Estimate the time spent: _____ minutes _____ seconds

Mark “1” for start of task, “2” for middle of task, “3” for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree — Completely Agree

Waypoint #4

Estimate the distance walked: ______ meters
Estimate the time spent: ____ minutes ____ seconds

Mark “1” for start of task, “2” for middle of task, “3” for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Waypoint #5

Estimate the distance walked: ______ meters
Estimate the time spent: ____ minutes ____ seconds

Mark "1" for start of task, "2" for middle of task, "3" for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree … Completely Agree

Waypoint #6

Estimate the distance walked: ______ meters
Estimate the time spent: ____ minutes ____ seconds

Mark "1" for start of task, "2" for middle of task, "3" for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Waypoint #7

Estimate the distance walked: _______ meters
Estimate the time spent: _____ minutes _____ seconds

Mark “1” for start of task, “2” for middle of task, “3” for end of task:

I knew **where I was**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I knew **where I was going**.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I felt **confident** about finding the goal.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I chose the tool I felt **made the most sense** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
The tools were **equally useful/useless** in the journey.	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree
I like having a **choice of tools**	|----------|----------|----------|----------|----------|----------|----------| Completely Disagree ... Completely Agree

Post-Experiment

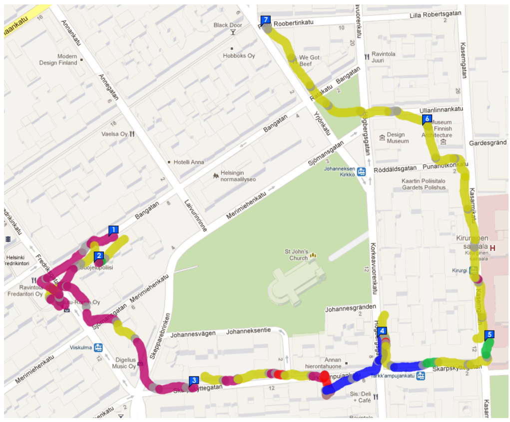
Please rank your interface preferences (1 = most preferred, 5 = least preferred):

Interface	Rank	When starting	Navigating	When near
Compass				
North Up Map				
Forward Up Map				
Augmented Reality				
Radar				

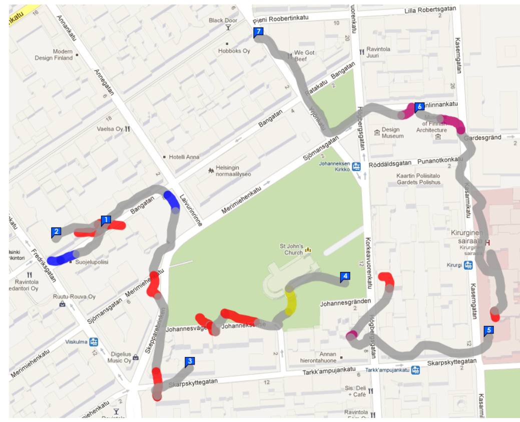
Please give some more detailed comments:

Thank you!!!

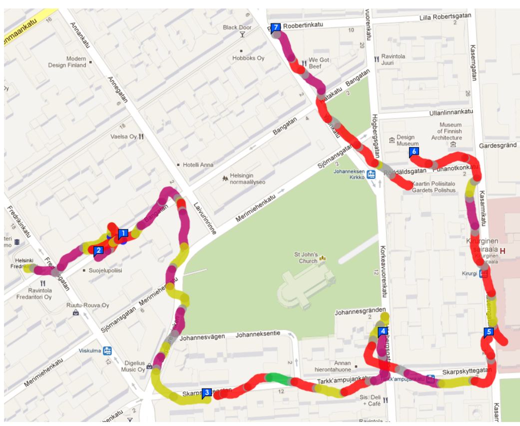
C
Nav2 Traversals



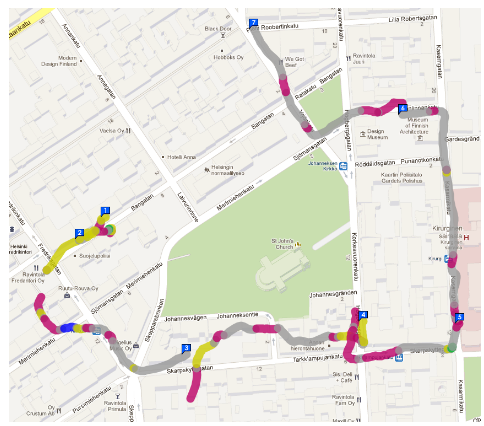
(a) Participant 1



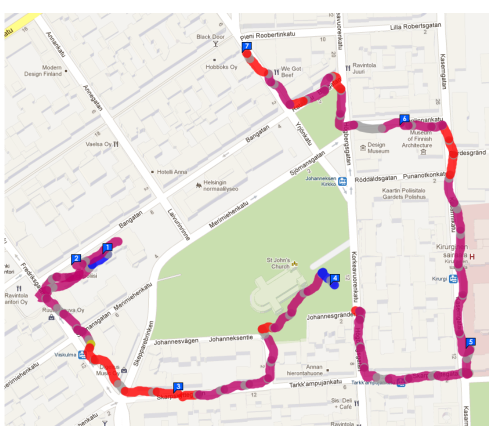
(d) Participant 4



(b) Participant 2



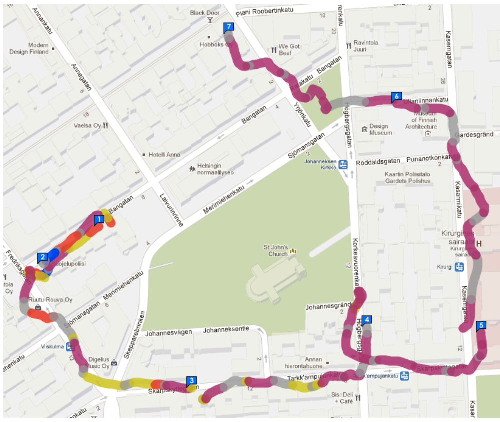
(e) Participant 5



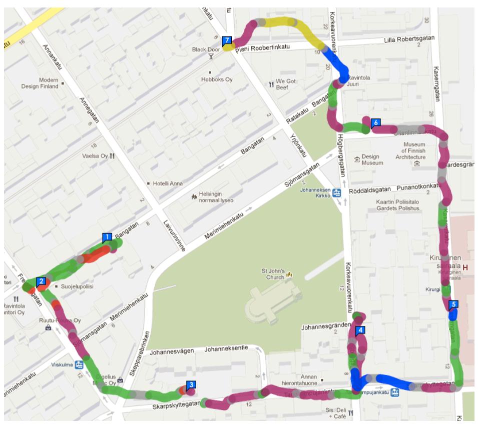
(c) Participant 3

(f) Participant 6

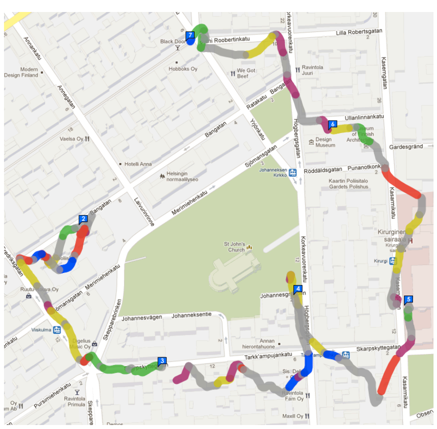
Figure C.1: Nav2 traversals for participants 1 through 6



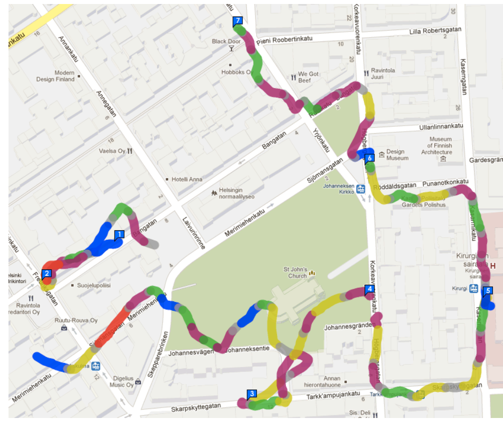
(a) Participant 7



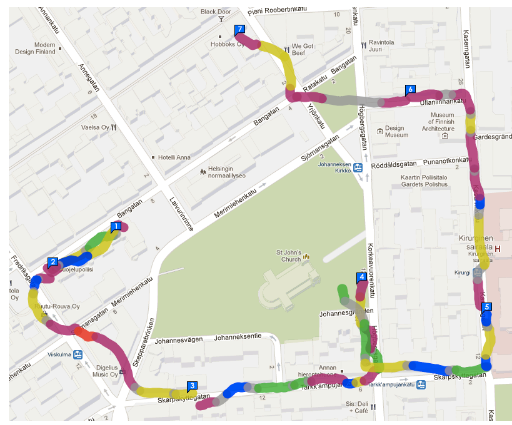
(b) Participant 8



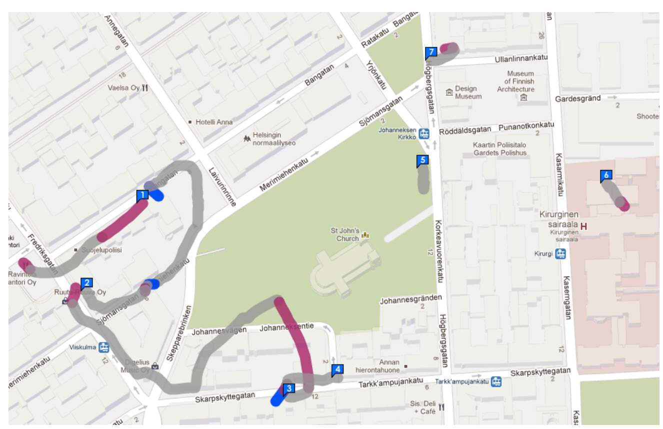
(c) Participant 9



(d) Participant 10



(e) Participant 11

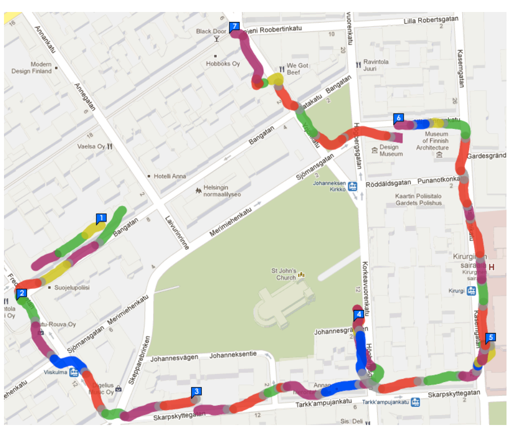


(f) Participant 12

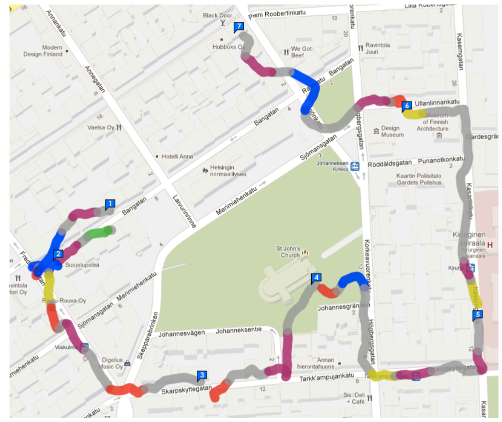
Figure C.2: Nav2 traversals for participants 7 through 12

(a) Participant 13

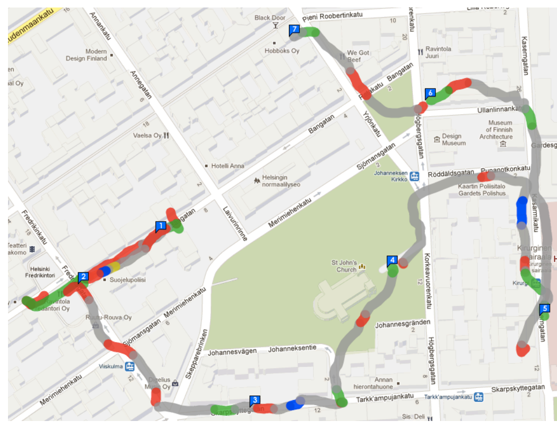
(b) Participant 14



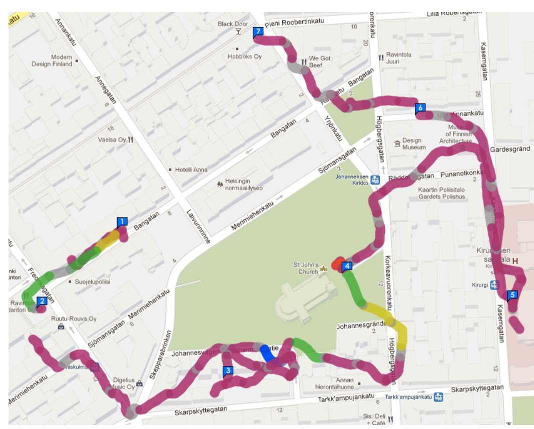
(c) Participant 15



(d) Participant 16



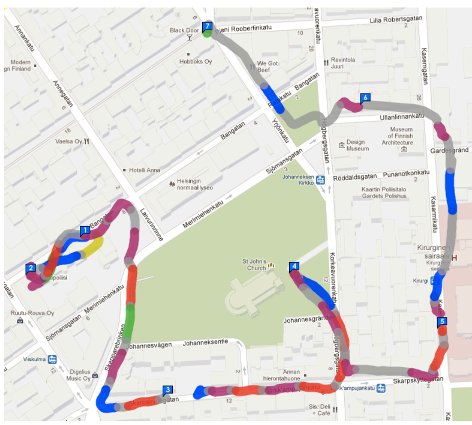
(e) Participant 17



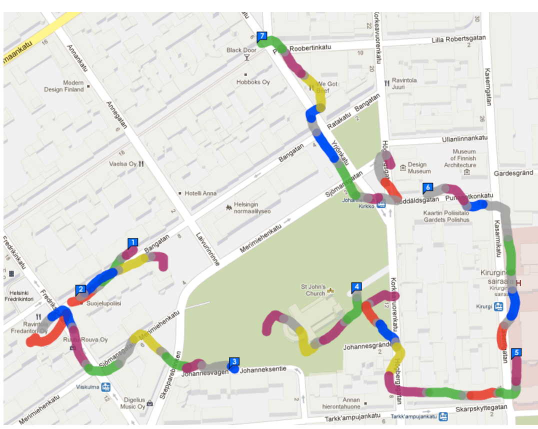
(f) Participant 18

Figure C.3: Nav2 traversals for participants 13 through 18

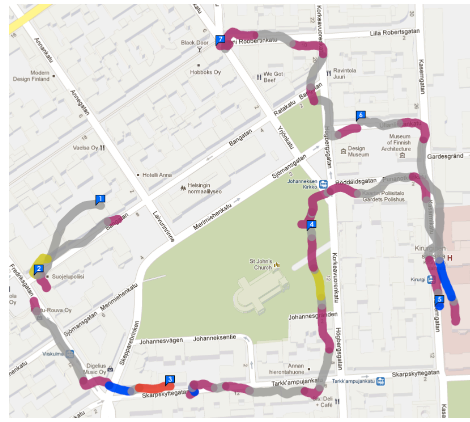
(a) Participant 19



(b) Participant 20



(c) Participant 21

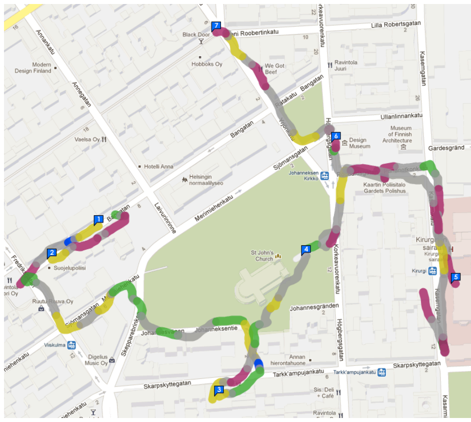


(d) Participant 22

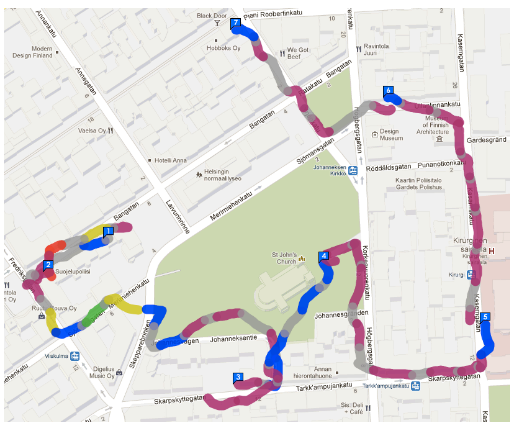
(e) Participant 23

(f) Participant 24

Figure C.4: Nav2 traversals for participants 19 through 24



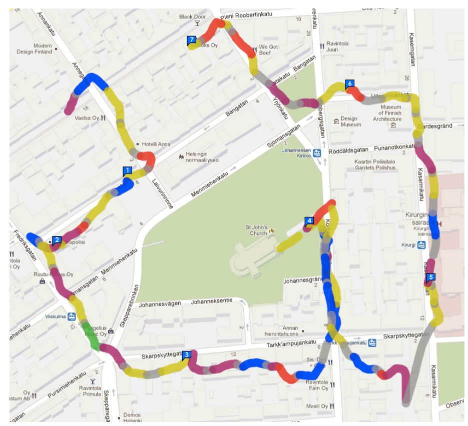
(a) Participant 25



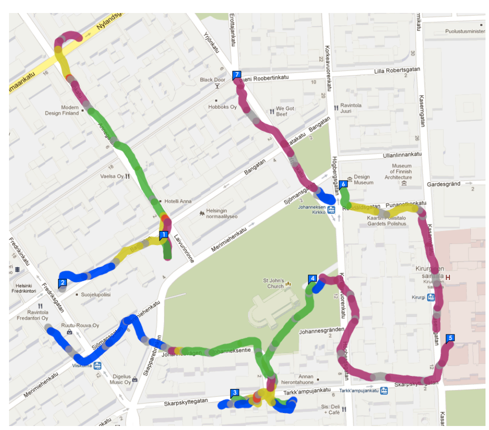
(b) Participant 26

(c) Participant 27

(d) Participant 28



(e) Participant 29

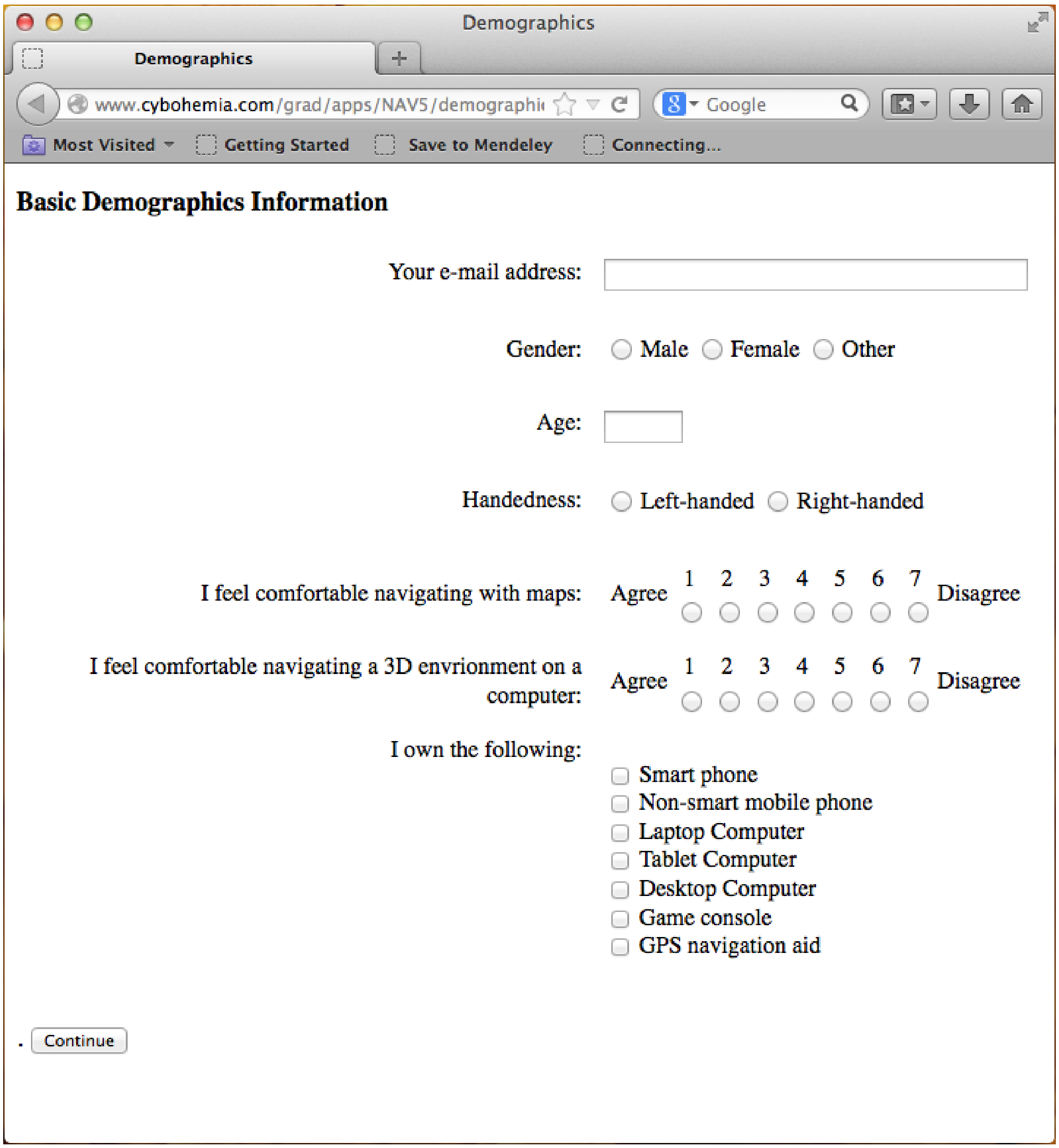


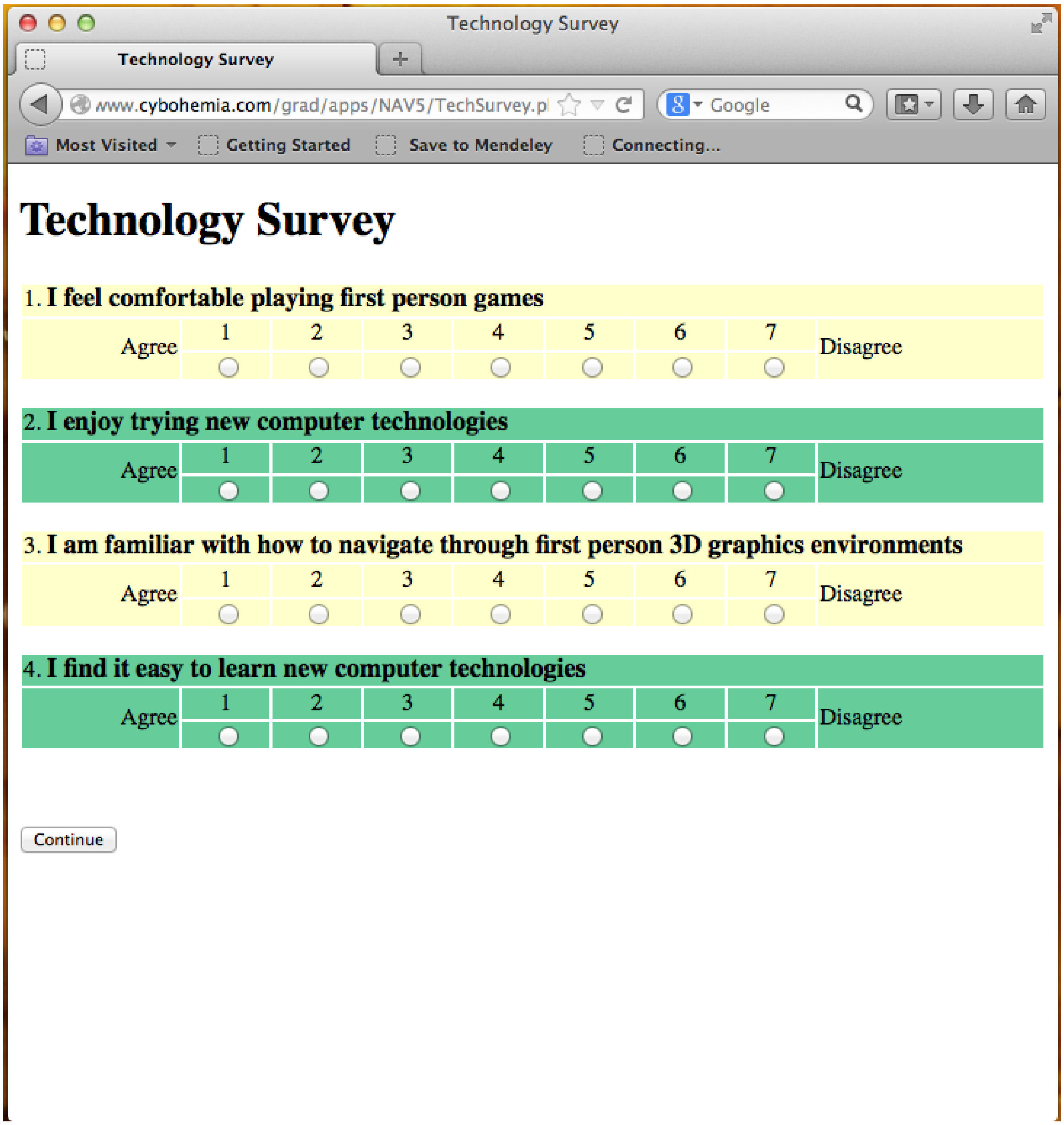
(f) Participant 30

Figure C.5: Nav2 traversals for participants 25 through 30

D

SPART Questionnaire


Demographics
Demographics
www.cybohemia.com/grad/apps/NAV5/demographic
Google
Most Visited
Getting Started
Save to Mendeley
Connecting...
Basic Demographics Information
Your e-mail address:
Gender: Male Female Other
Age:
Handedness: Left-handed Right-handed
I feel comfortable navigating with maps: Agree 1 2 3 4 5 6 7 Disagree
I feel comfortable navigating a 3D envrionment on a computer: Agree 1 2 3 4 5 6 7 Disagree
I own the following:
Smart phone
Non-smart mobile phone
Laptop Computer
Tablet Computer
Desktop Computer
Game console
GPS navigation aid
Continue



Technology Survey

1. I feel comfortable playing first person games

	1	2	3	4	5	6	7	
Agree	○	○	○	○	○	○	○	Disagree

2. I enjoy trying new computer technologies

	1	2	3	4	5	6	7	
Agree	○	○	○	○	○	○	○	Disagree

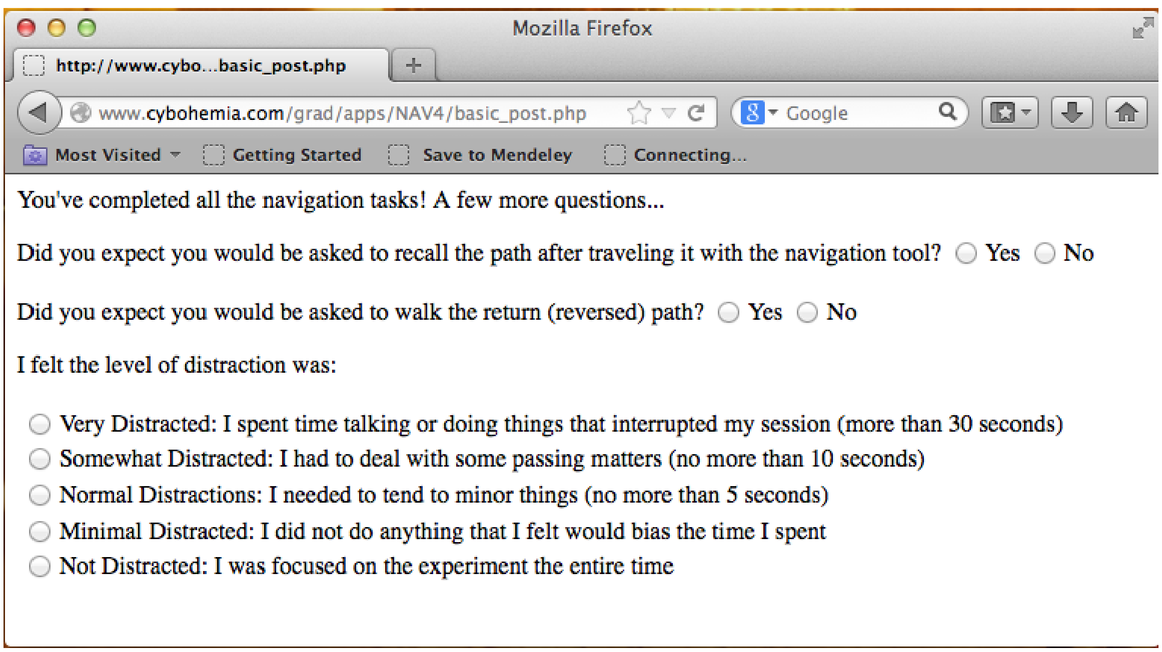
3. I am familiar with how to navigate through first person 3D graphics environments

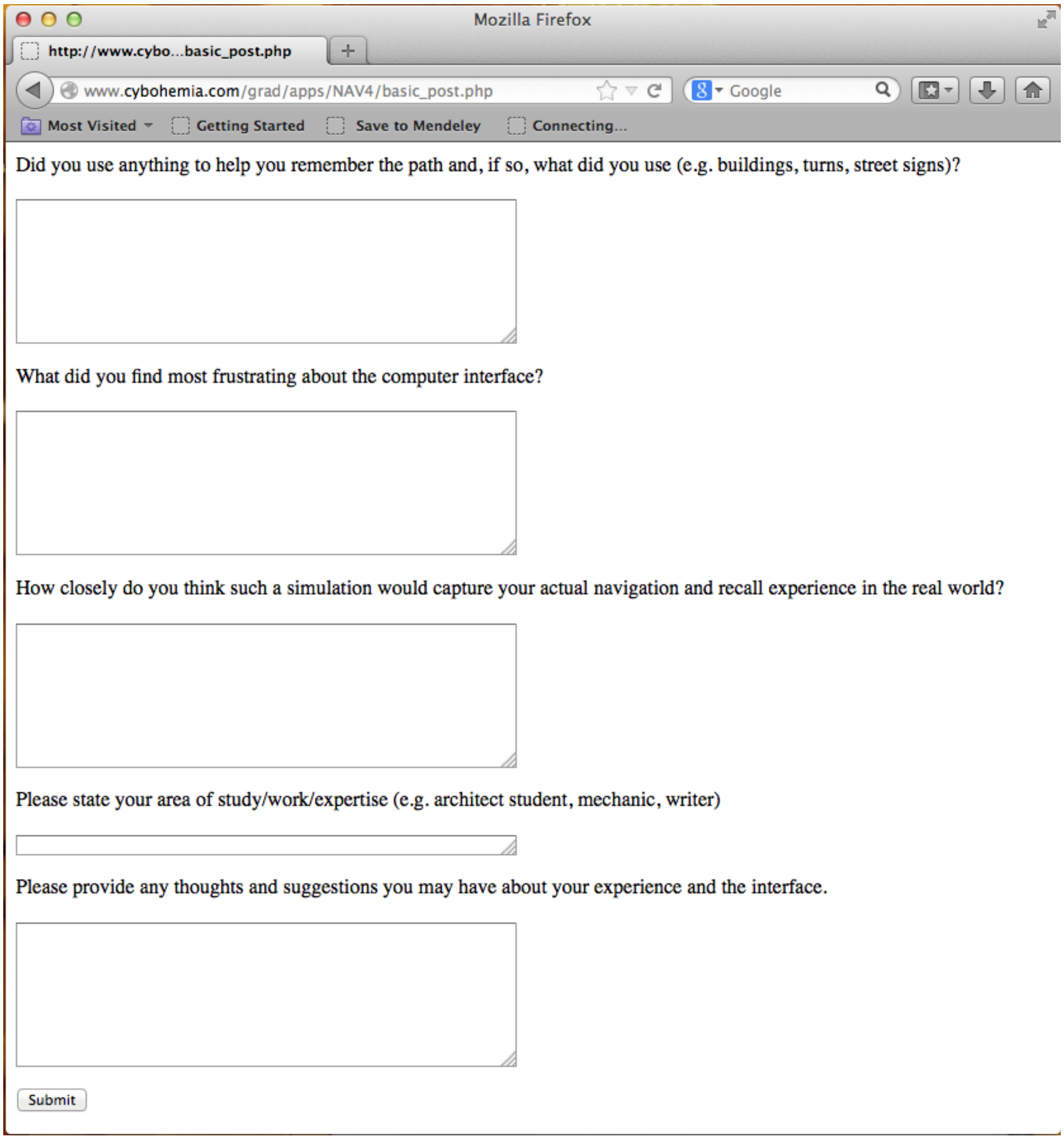
	1	2	3	4	5	6	7	
Agree	○	○	○	○	○	○	○	Disagree

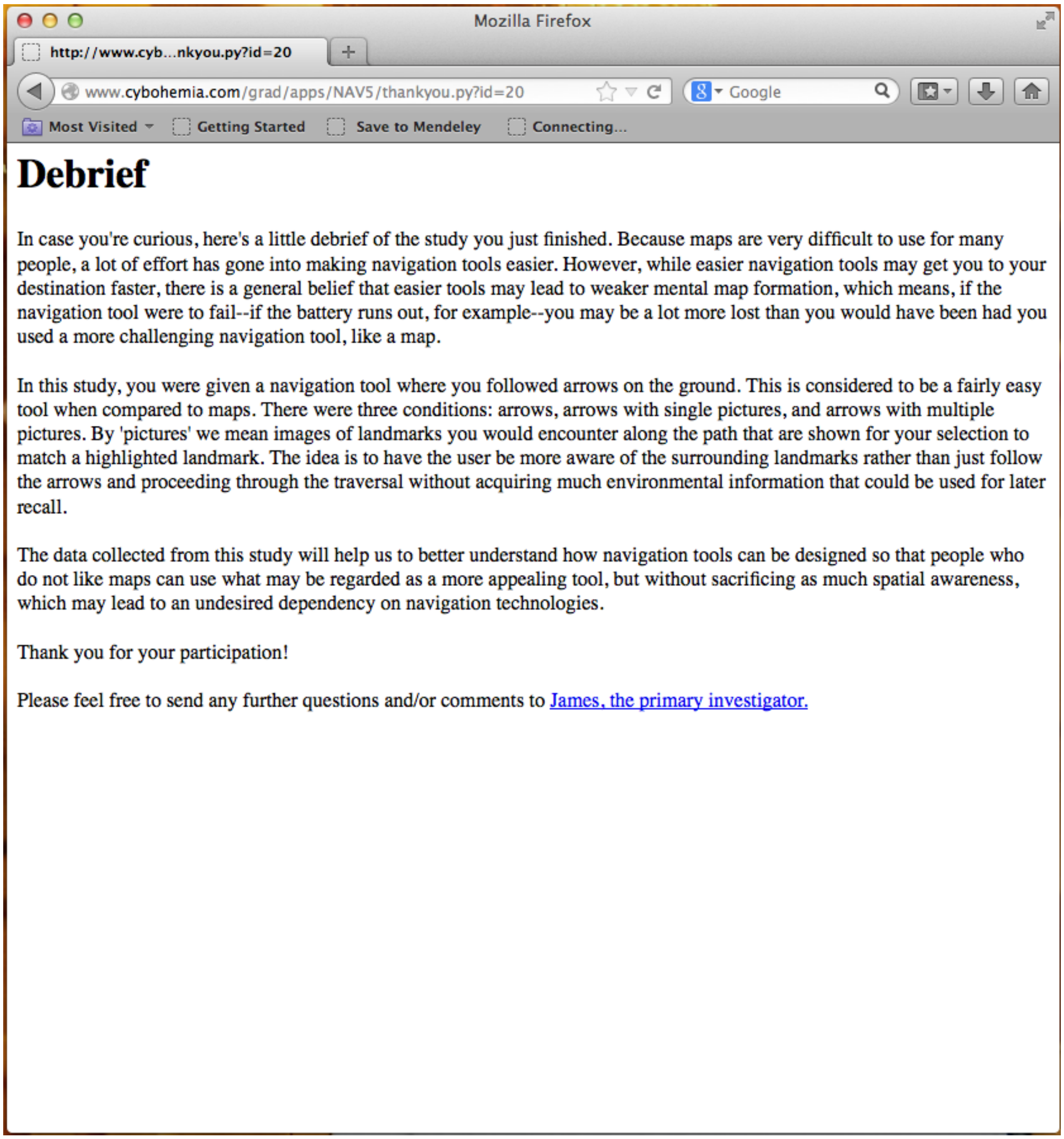
4. I find it easy to learn new computer technologies

	1	2	3	4	5	6	7	
Agree	○	○	○	○	○	○	○	Disagree

Continue


Mozilla Firefox
http://www.cybo...basic_post.php
www.cybohemia.com/grad/apps/NAV4/basic_post.php
Google
Most Visited
Getting Started
Save to Mendeley
Connecting...
You've completed all the navigation tasks! A few more questions...
Did you expect you would be asked to recall the path after traveling it with the navigation tool? Yes No
Did you expect you would be asked to walk the return (reversed) path? Yes No
I felt the level of distraction was:
Very Distracted: I spent time talking or doing things that interrupted my session (more than 30 seconds)
Somewhat Distracted: I had to deal with some passing matters (no more than 10 seconds)
Normal Distractions: I needed to tend to minor things (no more than 5 seconds)
Minimal Distracted: I did not do anything that I felt would bias the time I spent
Not Distracted: I was focused on the experiment the entire time


Mozilla Firefox
http://www.cybo...basic_post.php
www.cybohemia.com/grad/apps/NAV4/basic_post.php
Google
Most Visited
Getting Started
Save to Mendeley
Connecting...
Did you use anything to help you remember the path and, if so, what did you use (e.g. buildings, turns, street signs)?
What did you find most frustrating about the computer interface?
How closely do you think such a simulation would capture your actual navigation and recall experience in the real world?
Please state your area of study/work/expertise (e.g. architect student, mechanic, writer)
Please provide any thoughts and suggestions you may have about your experience and the interface.
Submit



Debrief

In case you're curious, here's a little debrief of the study you just finished. Because maps are very difficult to use for many people, a lot of effort has gone into making navigation tools easier. However, while easier navigation tools may get you to your destination faster, there is a general belief that easier tools may lead to weaker mental map formation, which means, if the navigation tool were to fail--if the battery runs out, for example--you may be a lot more lost than you would have been had you used a more challenging navigation tool, like a map.

In this study, you were given a navigation tool where you followed arrows on the ground. This is considered to be a fairly easy tool when compared to maps. There were three conditions: arrows, arrows with single pictures, and arrows with multiple pictures. By 'pictures' we mean images of landmarks you would encounter along the path that are shown for your selection to match a highlighted landmark. The idea is to have the user be more aware of the surrounding landmarks rather than just follow the arrows and proceeding through the traversal without acquiring much environmental information that could be used for later recall.

The data collected from this study will help us to better understand how navigation tools can be designed so that people who do not like maps can use what may be regarded as a more appealing tool, but without sacrificing as much spatial awareness, which may lead to an undesired dependency on navigation technologies.

Thank you for your participation!

Please feel free to send any further questions and/or comments to James, the primary investigator.

E

Santa Barbara Sense of Direction Questionnaire

SANTA BARBARA SENSE-OF-DIRECTION SCALE

Sex: F M   Today's Date:________________

Age:_______   V. 2

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

1. I am very good at giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.

strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.

strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I very easily get lost in a new city.

strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

strongly agree 1 2 3 4 5 6 7 strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

strongly agree 1 2 3 4 5 6 7 strongly disagree

11. I don't enjoy giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

12. It's not important to me to know where I am.

strongly agree 1 2 3 4 5 6 7 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

strongly agree 1 2 3 4 5 6 7 strongly disagree

14. I can usually remember a new route after I have traveled it only once.

strongly agree 1 2 3 4 5 6 7 strongly disagree

15. I don't have a very good "mental map" of my environment.

strongly agree 1 2 3 4 5 6 7 strongly disagree

F

NASA Task Load Index

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

G

System Usability Scale

System Usability Scale

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

H

Immersive SPART System Study

Our study of the SPART system, as described in Chapter 6, was deployed on desktop computers. Because users of desktop VE systems may out-perform users of more immersive systems with respect to interaction [17], we focused on streamlining the input interface, as noted. However, consideration from the perspective of the output display has been mixed. While it has been observed that the unlimited Field-of-Regard (FoR) of HMDs would contribute to greater spatial understanding [8], it has also been argued that desktop systems would yield better user performance due to a wider Field-of-View (FoV) [83]. Some studies, in fact, conclude that the two are substantially the same with respect to spatial knowledge acquisition [**?**].

In order to better understand how our studies may be affected by the level of immersion in the VE, we conducted an exploratory study of SPART deployed on an HMD.

H.1 Methodology

A standard desktop system can offer relatively high resolution but its FoR is approximately 45° [37], which effectively means that any slight change in a user's focus will return them back to the real world outside of the VE confined to the computer monitor. This makes it difficult for a user to become immersed in a VE. In contrast to this, HMDs allow users to look in any direction and remain in the VE. It does this by tracking head motion and simulating the corresponding change in the virtual world viewpoint. This effectively gives HMDs unlimited FoR.

We deployed SPART on the Oculus Rift HMD with a field of view of 90° and a full resolution of 1280x800 divided into two 640x800 images, one for each eye. The Rift also has an integrated three degree of freedom head tracker that provides the head orientation. Due to the relatively low resolution of the Oculus Rift, the legibility of the street signs was far lower than on the desktop system and the map navigation tool was difficult to read when presented as an inset. We therefore modified the street signs to be much larger, as shown in Figure H.1, and presented the map as a full-screen tool, as shown in Figure H.2.

Figure H.1: Street signs on the desktop (left) and HMD (right) systems.

While wearing the HMD the participants would be immersed in the virtual enviornment and not be able to visually see the objects around them in the real world, so we used a game controller for movement instead of the keyboard and mouse combination. The left and right thumbpads were used for forward movement and body turning, respectively, while the HMD turned the head. As with the desktop study, forward movement was always in the direction of where the user is looking. The left button was used to invoke the navigation aid.

It is well known that VE can induce motion sickness and this effect may be magnified in

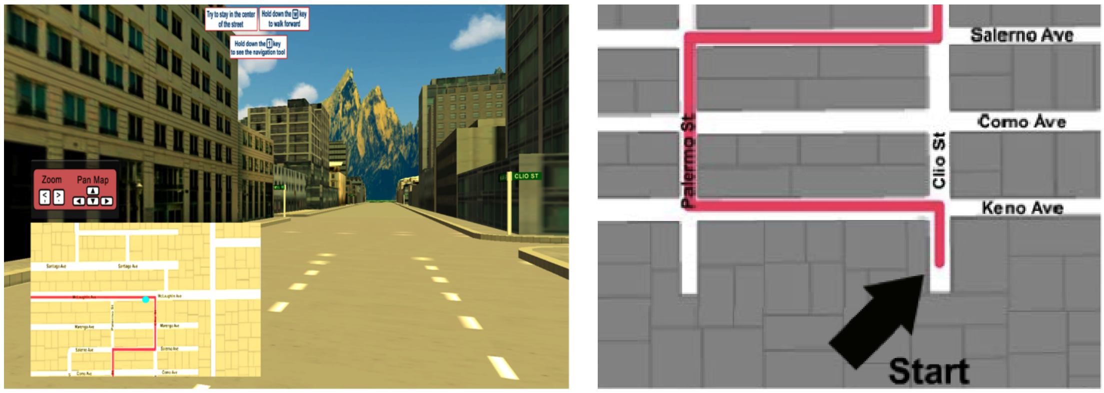


Figure H.2: Map interface on the desktop (left) and HMD (right) systems.

an immersive setting. Therefore, the speed of the simulation was adjusted to be consistent with the tracking of head movement, and set to 3 m/s, or 60% of the speed in the desktop study. Having detected the effects of motion sickness in early pilot tests, we chose to further avoid the possibility by reducing the traversal length and using only Path A. Additionally, due to various constraints and the observation that the effect for which we were studying was most pronounced between the MP and the AR conditions, we omitted the MY condition.

While the deployment platform was changed from a desktop system to an HMD, the experimental procedure remained unchanged and the reader is referred to Section 6.3 for relevant details.

H.2 Results

As with the desktop study, we compared the total Guided traversal times as well as navigation tool usage data and Unguided Recall traversal times between the interfaces. In this section, we report on the results of this exploratory study.

H.2.1 Participants

A total of 18 participants (6 females, mean age=25.83) successfully completed the HMD study. As with the desktop study, pre-test questionnaires and a training exercise were completed before the experimental trials began. Due to the greater possibility of motion sickness as well as the physical gear required, participants were encouraged to take rest breaks–where they can removed the HMD–between the segments of the experiment.

H.2.2 Guided Performance

adjustment noted above to allow comparisons against the desktop results. Analyses of variance were applied to the results and Bonferroni post hoc analyses were applied to identify pair-wise significant differences.

The performance times agreed with our desktop study: the average traversal time for map users ($M = 395.33s, SD = 129.06s$) was significantly longer than for AR users ($M = 293, 89s, SD = 39.18s$), to a $p < .05$ level. This is shown in Figure H.3.

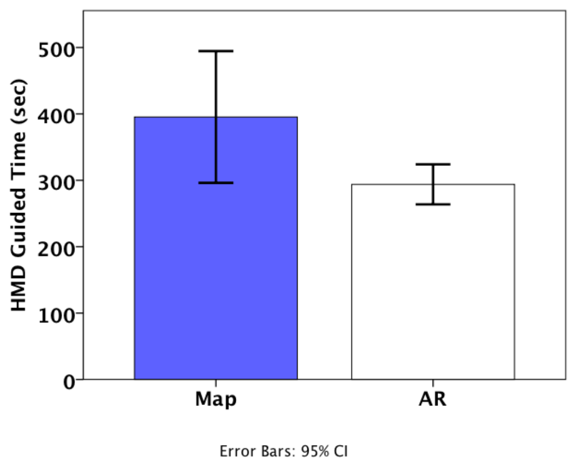
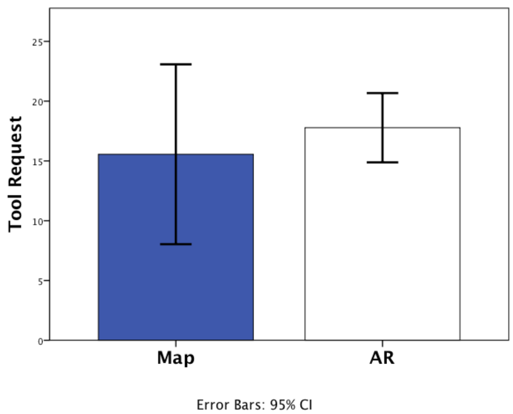


Figure H.3: Traversal times with HMD.

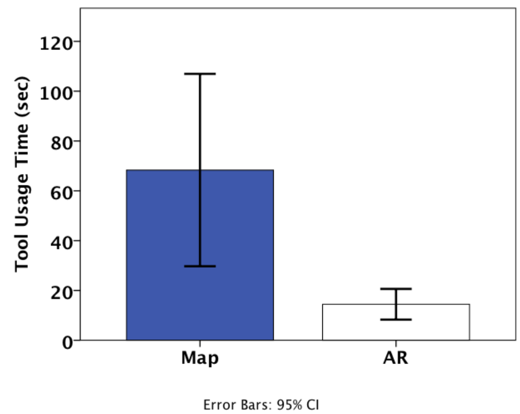
H.2.3 Tool Usage

The number of times the MP tool was invoked ($M = 15.56, SD = 9.79$) was only slightly less than the AR condition ($M = 17.78, SD = 3, 77$) and the two were not statistically significantly different, as shown in Figure H.4a.

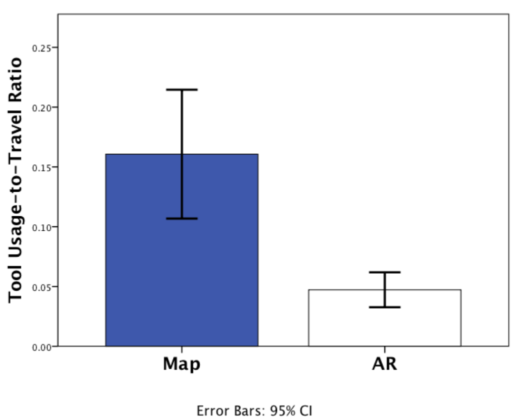
However, MP users spent significantly longer referring to the navigation tool ($M = 68.33s, SD = 50.26s$) than AR users ($M = 14.44s, SD = 8.02s$) with $p < .05$, as shown in Figure H.4b.



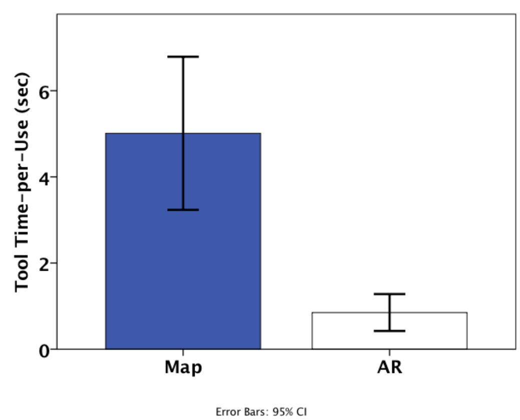
(a) Request count for Path A



(b) Request count for Path B



(c) Total usage time for Path A



(d) Total usage time for Path B

Figure H.4: HMD navigation tool usage.

Significant differences were also detected in the ratio of time spent using the navigation tool to the time spent traveling through the VE. MP users spent significantly more time using the navigation tool ($M = 16.07\%, SD = 7\%$) than AR users ($M = 4.72\%, SD = 1.9\%$) to the $p < .01$ level, as shown in Figure H.4c. The average time spent per invocation of the navigation tool was also significantly different between the interfaces. MP users spent far longer per use ($M = 5.01s, SD = 2.31s$) than AR users ($M = .85s, SD = .56s$) to the $p < .01$ level, as shown in Figure H.4d.

H.2.4 Unguided Recall Performance

The average unguided times for HMD users showed no statistically significantly differences between the two interface conditions. For MP users ($M = 324.00s, SD = 47.07s$) while for AR users ($M = 324.22s, SD = 58.84s$). This is shown in Figure H.5.

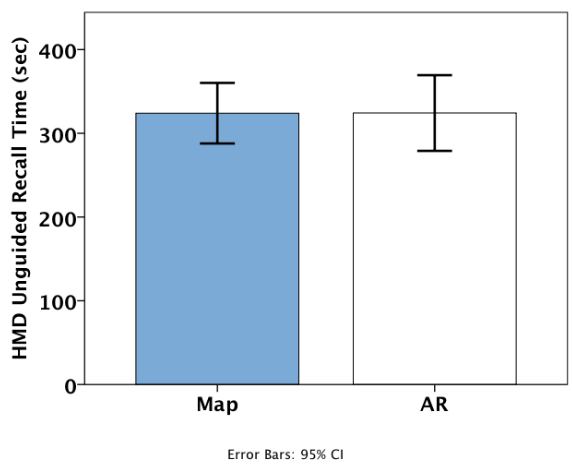


Figure H.5: Performance times for HMD recall traversals.

With respect to differences in times between the guided and unguided traversals, the map users showed a drop in traversal time while the AR users remained about the same. This is shown in Figure H.6.

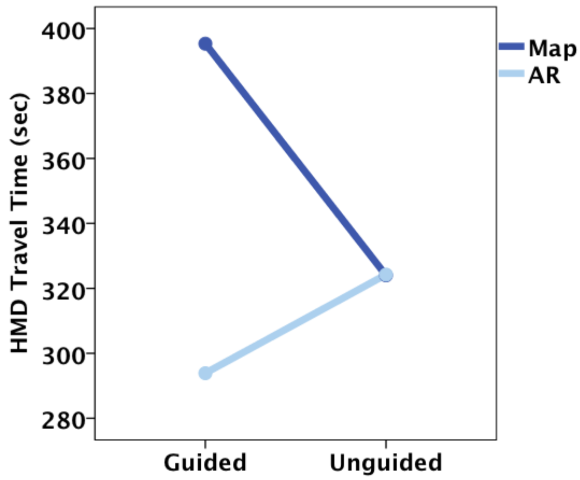


Figure H.6: Performance times between HMD guided and recall traversals.

Navigation Accuracy

In the HMD environment a greater number of errors was observed with map users than with AR users, as shown in Figure H.7. The difference in errors made for guided users were significant between map users ($M = 1.44, SD = 2.13$) and AR users ($M = .11, SD = .33$). The difference during the unguided recall was statistically insignificant between map users ($M = 1.56, SD = 1.33$) and AR users ($M = 2.44, SD = 2.19$). Comparing guided and unguided traversals, map users exhibited no significant differences in errors made during the guided traversal while AR users had a significant difference to the $p < .05$ level.

H.3 Discussion

Although the HMD offered an immersive experience that is arguably more realistic, its lower resolution may have hampered user performance. Table H.1 shows a possible consequence of this: the average performance time for the HMD Map tool was substantially longer than the desktop case from the Nav3 study described in Chapter 6.

It is possible that the map interface created for the HMD to accommodate its lower resolution may have been the primary factor for the prolonged time. Its need to use the full

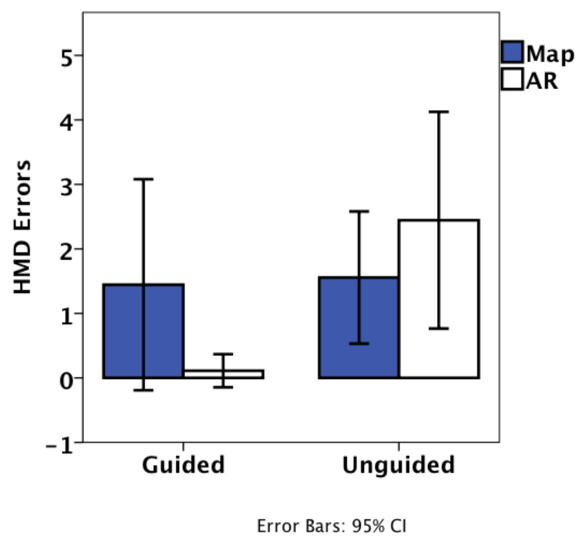


Figure H.7: Comparison of errors made during guided path traversal and unguided path recall for HMD participants.

screen would have prevented users from making visual correspondences between the map and the surroundings without having to switch from walking mode to navigation mode. With higher resolution, an inset map could be functionally usable and HMD users would be able to refer to both the actual landmarks and their representations in one view. This would make the HMD user experience closer to the Desktop user experience and so it is possible that the time required for the traversal for HMD map users may decrease enough to be comparable to the other recorded times.

We saw earlier that the HMD MP condition, where the map took up the full viewable screen, took substantially longer than all other guided conditions (see Table H.1). In addition to prolonging the traversal time, the dissociation of the map from the surrounding environment may also have increased the chances of making erroneous turns. It is possible that users who made wrong turns during the guided traversal will confuse the correct and incorrect turns when recalling the paths and therefore commit a higher number of errors in the recall, as well.

Our studies indicate that the choice of platform may have considerable impact upon usage behavior. Although the HMD offered unlimited FoR, display resolution and FoV are

Tool	Time
Desktop MP	$M = 187.25s, SD = 16.88s$
HMD MP	$M = 264.53s, SD = 94.61s$
Desktop AR	$M = 182.53s, SD = 25.67s$
HMD AR	$M = 182.11s, SD = 26.50s$

Table H.1: Traversal times for Desktop Path A and HMD path. The HMD data was calibrated to account for the speed difference. The Desktop data was taken from participants who traversed Path A before Path B in the desktop trials, which would make it comparable to the experience of the HMD participants.

also important factors, as noted in [8]. In fact, it has been observed that while many users prefer the HMD experience, they more often perform better on desktop systems due to the nature of the interaction [17]. In our studies, MP was requested significantly less than AR for Desktop users but, for HMD users, the requests were almost the same for the two interfaces. The need to compensate for the low resolution with a full-screen map altered the usage behavior for the MP condition for the HMD—possibly to the extent that the recall is diminished.

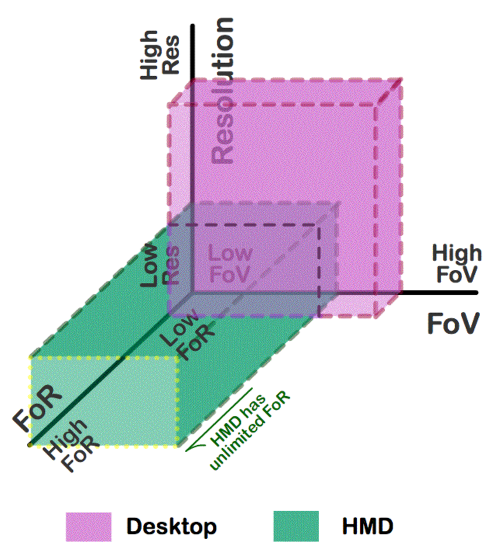


Figure H.8: Three major contributors for immersiveness plotted along independent axes.

Our results suggest that choosing a VE platform for navigation studies may not be straightforward given the different strengths and a consequential lack of a clear overall superior testing platform, with respect to immersiveness. As depicted in Figure H.8, a desktop VE offers higher resolution and FoV than an HMD VE. On the other hand, HMDs offer infinite FoR, which greatly enhances a perception of immersion. The relevant question is: which factors are more important for a user when navigation and spatial knowledge are the primary consideration? Further investigation into the suitability of an immersive environment for our studies was deemed beyond the scope of this thesis since our focus on navigation and acquisition of spatial knowledge may be sufficiently—if not better—captured with desktop systems when compared to HMDs.

I

Dual Task Word List

The following words were used in thje NAV4 dual-task study. The word list consisted of sixty English words used in the dual-task climbing study by Green and Helton [23]. Thirty nonsensical words were added to this list to act as distractors and participants were instructed to ignore the nonsensical words (shown in plain typeface, below) while memorizing the recognizably English words (shown in bold, below). Words were shown in the order given to all participants.

ankle saloon xxjtr **icebox** qwxyzz bpblpp **slipper infant** xxqrst **mucus pudding hostage** lvvpdo **banner bullet sulphur** tkxjrq **doorman locker piano sunburn** lmmlppq gbvbpx **missile thicket monarch cowhide** kxwubg **leopard** dlkkgs ppkqqr **piston butcher** fffddo **fiord typhoon nectar** vvxprs **harness** ptttx **reptile lobster rattle** tqqtqt **bandit pepper** qpxqpp **morgue trumpet singer** kgplpk rstrts **blister jelly salad** wpklpl nmnmpq **settler sultan fabric lemon hamlet** btppt **shotgun** qrpprp **abode poster** bptxpr **cigar painter** hlkkpl **steamer sunset** rtpwp **costume bagpipe banker** rpqdb **spinach** bgbdpd **hairpin beggar** rbtsv qprtpq **skillet invoice robber** mngplq **kettle glacier**